

## Research Article

# Miracle: The Multi-Interface Cross-Layer Extension of ns2

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We present Miracle, a novel framework which extends ns2 to facilitate the simulation and the design of beyond 4G networks. Miracle enhances ns2 by providing an efficient and embedded engine for handling cross-layer messages and, at the same time, enabling the coexistence of multiple modules within each layer of the protocol stack. We also present a novel framework developed as an extension of Miracle called Miracle PHY and MAC. This framework facilitates the development of more realistic Channel, PHY and MAC modules, considering features currently lacking in most state-of-the-art simulators, while at the same time giving a strong emphasis on code modularity, interoperability and reusability. Finally, we provide an overview of the wireless technologies implemented in Miracle, discussing in particular the models for the IEEE 802.11, UMTS and WiMAX standards and for Underwater Acoustic Networks. We observe that, thanks to Miracle and its extensions, it is possible to carefully simulate complex network architectures at all the OSI layers, from the physical reception model to standard applications and system management schemes. This allows to have a comprehensive view of all the interactions among network components, which play an important role in many research areas, such as cognitive networking and cross-layer design.

## 1. Introduction

In the last few years, advances in the hardware for wireless networking and, especially, embedded microprocessor technologies have made it possible to manufacture very small radio equipments at low cost. This has enabled the integration of different technologies in a single mobile terminal. These multi-technology solutions are now available on the market and open up the possibility of exploiting new communication paradigms. Also, as multi-interface hardware becomes available at low cost, there is a parallel need for understanding its performance limits and devising new networking protocols that will make full use of the offered potential. Often, these systems are way too complex to be fully characterized analytically, and we have to resort to simulation tools for a more comprehensive understanding.

As a consequence of these facts, there has been an increasing need for investigation tools, in particular network simulators, to be conveniently exploited for these research purposes. Many are the features that researchers seek in network simulators. In this paper, we focus on the issues

which in our opinion are not addressed to a great extent by current network simulators. These issues are the following.

(1) *Accurate channel and PHY layer modeling*: recently, there has been an increasing need for accurate modeling of channel and PHY layer aspects. While simplified models, such as the disk propagation model, are still useful in some contexts, a general purpose simulator is nowadays expected to provide more realistic representations of the signal propagation and reception processes.

(2) *Modeling of a complete system*: the increasing complexity of communication systems has made performance evaluation a truly complex task, due to the fact that subtle interactions among the different components of the system can play an important role in determining its overall performance. These interactions are often not clear when only one or a few of the system components are modeled in isolation. This is a crucial issue in many novel research areas, such as cross-layer design [1, 2] and Cognitive Networking [3–5]. For this reason, a good general purpose network simulator is nowadays expected to provide means to model a complete communication system, from channel and PHY

layer all the way through the protocol stack up to the application layer.

(3) *Rapid prototyping of new wireless technologies*: new wireless technologies have been proposed and released at an amazing pace in recent years, and it is commonly the case that researchers struggle to develop simulation tools in a timely fashion to study these technologies as they emerge. In the past, the majority of the code for wireless networking simulation (especially at the PHY and MAC layers) has mainly been designed for specific technologies, without addressing code reusability during its design phase. The ns2 simulator, in particular, was not originally designed to simulate wireless networks, and support for this has been added only in a second phase, and in a rather improvised and nonsystematic way. As a consequence, the task of properly designing and developing code for the simulation of new wireless technologies is time consuming. Though wireless systems can overall differ significantly from each other, it is to be noted that there are many aspects and components of the PHY and MAC layers which are very similar across different technologies. An ideal simulator would treat these components through the same set of procedures and would leverage on well-defined Application Programming Interfaces (APIs) for PHY and MAC modules to allow easier and faster development of simulator code. All of this should be done with a particular emphasis on code modularity and reusability.

(4) *Spectrum awareness*: recently, research in fields such as Cognitive Radio, Ultra Wide Band, MultiCarrier Modulation schemes, and Underwater communications systems has created a strong need for network simulators to provide a better modeling of the Radio Frequency aspects of communications systems, such as spectrum occupation, RF filtering and inter-channel interference. State-of-the-art network simulators such as ns2 lack support for a correct modeling of how communication systems make use of the frequency spectrum.

(5) *Intertechnology interference*: unlicensed bands, in particular the 2.4 GHz ISM band, are characterized by the simultaneous presence of different wireless technologies interfering with each other; this is the case of popular wireless communication technologies such as IEEE 802.11, Bluetooth, and WiMAX, as well as noncommunicating technologies such as microwave ovens. Therefore, the introduction of spectrum awareness in wireless network simulators should be made in such a way to allow proper accounting of how different technologies interact among themselves in the propagation medium. We note that this goes beyond the issues discussed above. In fact, support for spectrum awareness in a single-technology scenario can be introduced by performing custom modifications to the code implementing that particular technology, while the simulation of Intertechnology interference requires that all technologies use the same representation of interference and spectrum usage.

(6) *Multi-technology multi-interface communication capabilities*: as more and more devices nowadays are equipped with multiple interfaces using different communication technologies, network simulators should provide support

for proper modeling of these scenarios, by means of a flexible and modular protocol stack architecture together with proper support for the development of the control modules which are needed to manage such a complex architecture.

(7) *Support for cross-layer interactions and optimizations*: while traditional networking strongly relied on protocol layer encapsulation to cope with system reliability and complexity issues, in recent years wireless networking research has shown that superior performance can actually be achieved by exploiting cross-layer optimization, that is, by optimizing the behavior of the whole communication system making different protocol layers interact with each other. Cross-layer optimization has now become a widely accepted paradigm among researchers, and for this reason it is very important that Network Simulators provide means to support the prototyping and testing of cross-layer solutions.

(8) *Support for heterogeneous networks*: while traditional networking research mainly focused on homogeneous networks, such as infrastructured, ad hoc, and mesh networks, in recent years there has been an increasing interest in scenarios in which these types of networks coexist. Simulating this type of scenarios today is very challenging, in particular due to the fact that the routing layer of state-of-the-art simulators is mainly designed for homogeneous networks. As a consequence, there is a need for supporting this type of heterogeneous network composition at all the layers of the protocol stack.

In this paper we present Miracle, an extension for the ns2 simulator that we developed with the aim of solving the above issues and therefore facilitating the simulation of modern communications systems. Our framework is called *Multi InterfAce cross-layer extension* (Miracle) for ns2 [6]. It is conceived as a set of additional dynamic libraries which provide ns2 with support for multi-technology and cross-layering. Our architecture is highly modular as it allows the interconnection of multiple down and upstream modules at every layer of the protocol stack. In addition, a dedicated communications facility provides the protocol stack of each node with cross-layer interaction capabilities. After discussing Miracle, we also present an additional framework for the simulation of the physical and medium access layers, developed on top of Miracle.

This paper is structured as follows. The next Section 2 presents the Miracle framework along with its main features. In Section 2.1, we start with a discussion of the related literature, where we motivate our work and contrast it with existing approaches. Subsequently, in Section 2.2 we delve into the description of the Miracle's node architecture and of its offered benefits in terms of modularity, cross-layer support, and extensibility. In Section 2.3, we discuss how existing ns2 modules can be reused within our framework. Furthermore, in Section 3 we describe the Miracle PHY and MAC extension, which we developed to allow accurate, flexible and reusable modeling of physical propagation channels and channel access procedures. In Section 4, we review existing implementations of wireless technologies in Miracle. Section 5 gives a quick overview of the projects that used Miracle and Section 6 concludes the paper.

## 2. Miracle

*2.1. Related Work.* The main motivation that led us to the development of this library was the need for a flexible and easy to use tool for the simulation of multilayer and multistack architectures in mixed wired/wireless settings. In this respect, there have recently been a few attempts to add flexibility to ns2, and in particular to overcome the current ns2 limit of no more than one wireless interface per mobile node. For example, TENS [7], Hyacinth [8], and the solution proposed by Agüero and Pérez [9] are extensions to ns2 which introduce the possibility of using multiple wireless interfaces within the same mobile node; however, they are currently limited to the use of the same radio technology (namely, IEEE 802.11) for all wireless interfaces. MW-Node [10], in addition to the support for multiple wireless interfaces, also allows coexistence of different radio technologies and routing protocols within the same node; still, its scope remains somewhat limited, since modularity is addressed only at the network layer and below, and the fixed protocol stack architecture of ns2 is maintained.

We note that the recently started ns3 project [11] shares with Miracle some relevant goals, such as enhanced modularity of components, while at the same time addressing some particular ns2 issues, such as support for distributed simulation and emulation, which are not considered in Miracle. Nevertheless, this choice for ns3 has required a complete rewrite of the simulator, which prevents reusability of the many valuable components already implemented for ns2. Miracle on the other hand, allows the reuse of ns2 code and can consequently exploit many of the features already included in ns2 with little or no development effort, as we will discuss in Section 2.3. Furthermore, ns3 tries to mimic as close as possible the protocol stack of real systems (in particular Unix systems), whereas Miracle gives total freedom to the researchers in specifying the way in which their protocol stack is built. Finally, while in ns3 cross-layer functionalities have to be implemented using general purpose tools such as Packet Tags and Callbacks, Miracle provides a dedicated framework to handle cross-layer interactions, which makes it easier to implement not only complex cross-layer optimization solutions, but also automatic discovery and configuration of modules at runtime, which turns out to be very effective in reducing the time taken to configure the simulator through dedicated scripts.

*2.2. Miracle Node Architecture.* One of the primary goals of Miracle is to facilitate the interconnection of different protocol modules while uniforming the procedure by which multiple protocol layers are plugged into the same node. We may define, for instance, a node with multiple PHY, MAC, or routing modules and we may use all of them in the same simulation by making decisions on which ones to use at runtime. This is the typical case of, for example, advanced radio resource management (RRM) schemes, which has to efficiently make a decision on which interface(s) is to be used in order to meet quality of service (QoS) requirements for the users.

We started our work from a few existing ns2 classes that were extended to obtain the basic building blocks of our framework. The reason for this choice was to maintain backward compatibility with previously developed ns2 code. In Figure 1, we show a diagram of the Miracle node architecture. One of the most important blocks is probably the Module class. As shown in the left side of this figure, multiple Modules can coexist within the same protocol layer and can be connected to up and downstream Modules. Each Module contains a specific protocol or entity which may be a PHY, MAC, routing layer, transport protocol, application, and so forth. The Module class provides the following methods for the communication with adjacent Module instances:

- (i) `sendDown(Packet* p, double delay = 0)` and `sendUp(Packet* p, double delay = 0)` are used to send a Packet, respectively, to the Module(s) below and above with, possibly, a delay. Using these two methods, a copy of the Packet is delivered to each of the up or downstream Modules.
- (ii) `sendDown(int moduleId, Packet* p, double delay = 0)` and `sendUp(int moduleId, Packet* p, double delay = 0)` allow to send Packets to a specific Module below and above, respectively. In this respect, we note that Module instances are automatically assigned a unique identifier; and a Module instance can know the identifier of other instances either statically from configuration or dynamically by using a discovery process at run time.

Dedicated objects, referred to here as Connector-Traces, are automatically allocated by Miracle to allow communication across Modules through the above methods. Hence, the user is only responsible for specifying where each module appears in the protocol stack, and what other module it needs to connect to; the necessary connectors are put in place and configured automatically. In this case, since we are referring to standard OSI communication, we used a specific extension of the ConnectorTrace called SAP.

All Modules within the same stack are connected to a unique structure called NodeCore. The role of the NodeCore is twofold: (1) first, it enables communication among Modules and thus facilitates cross-layer design and (2) the NodeCore manages information coming from the Modules and provides functionalities of common interest for all or a group of them.

Regarding cross-layer interactions, we note that the common practice in standard ns2 consists of either including control messages within packet headers (e.g., as done in [12]) or manipulating the ns2 node structure in a rather ad hoc manner (as is the case for several ns2 extensions which are discussed in [10]). In the former case, however, control messages would be tightly bound to the packet flow, whereas in the latter, it would likely be difficult to adapt the code to additional needs. Note that these are static solutions as communication interfaces among modules and cross-layer algorithms must be defined in advance, that is, during

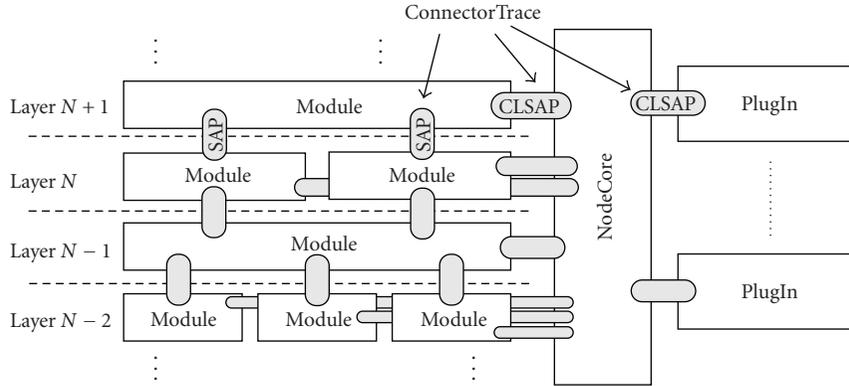


FIGURE 1: Example of a general multilayer architecture within the Miracle framework.

the development of each module. In ns3, this functionality can be achieved by means of Callbacks. However, the need for explicitly connecting all callbacks puts a significant burden on the user. Furthermore, this strategy only allows one-to-one interactions where the communicating entities are known at configuration time. Actually, in ns3, also Packet Tags can be used to exchange cross-layer messages; however, this practice consists of piggybacking cross-layer information onto data packets, and for this reason its applicability is limited to those cross-layer interactions which happen concurrently with data exchange.

In contrast, the solution provided by Miracle adheres to the widely accepted concept of having a bus for interlayer communication [1]. This makes it possible to exchange messages among Modules at any time and without the need for interleaving them with the data flow. The way in which cross-layer information is exchanged is defined by the `C1Message` abstract base class, which provides means for addressing cross-layer information among modules within the same node. In particular, a `C1Message` can be addressed to a particular module (unicast `C1Message`), to all modules in the node (broadcast `C1Message`), or to all modules within the same layer (layercast `C1Message`); in all these cases, the routing of `C1Messages` is performed by the `NodeCore` through a specific extension of the `ConnectorTrace` class called `CLSAP` (i.e., cross-layer SAP). Furthermore, a `C1Message` can be addressed from a module to the modules in the layer immediately above or below it; in this case, the message is routed directly by the SAP between modules. The applications of this last type of cross-layer messaging are very useful for automatic configuration purposes; for instance, the routing layer can discover, during the simulation, which radio interfaces are available, by just sending a `C1Message` to all the modules in the layer below. The interface provided by the `Module` class for the `C1Message` management includes the following methods:

- (i) `sendAsyncC1MsgDown(C1Message* m, double delay = 0)` and `sendAsyncC1MsgUp(C1Message* m, double delay = 0)`: these methods allow to send `C1Messages`, respectively, to the Modules below and above in an asynchronous fashion,

that is, each method returns immediately and the `C1Message` will be scheduled for later delivery according to the specified delay.

- (ii) `sendSyncC1MsgDown(C1Message* m)` and `sendSyncC1MsgUp(C1Message* m)`: these allow to send `C1Messages`, respectively, to the Modules below and above in a synchronous fashion, that is, each method returns only after the `C1Message` has been delivered and processed by all receiver Module(s).

As to the maintenance of common information and functionalities, the `NodeCore` currently maintains the geographical position for each node. To this end, we defined a generic interface which can be used for the implementation of mobility models directly in C++. Currently, the framework features deterministic and Gauss-Markov [13] mobility models.

Another important piece of the architecture is the `Plugin` class. `Plugins` are attached to the `NodeCore` and are the perfect place for cross-layer algorithms, for example, resource radio management modules, cognitive engines, decision logic for the selection of optimal protocol parameters, and so forth. Thanks to `C1Messages`, control messages can be easily exchanged between `Plugins` and protocol Modules. In this case, the interface implements the methods `sendSyncC1Msg` and `sendAsyncC1Msg` to delivery `C1Messages` to the intended destination(s) in asynchronous and synchronous fashions.

Finally, Miracle implements a brand new tracing technique: all packets and cross-layer messages are traced by each specific extension of `ConnectorTrace` as they pass through it. Hence, the development of tracing functionalities is not bound to the implementation of Modules. The level of verbosity of message traces is fully tunable and programmable. With tunable, we mean that the tracing functionality can be independently turned on/off for each `ConnectorTrace`. Programmable means that the output of the tracers can be fully defined by the user. Accordingly, each implementation of a `Module/Plugin` can define its own tracing rules, which can be exploited for debugging or collection of statistics.

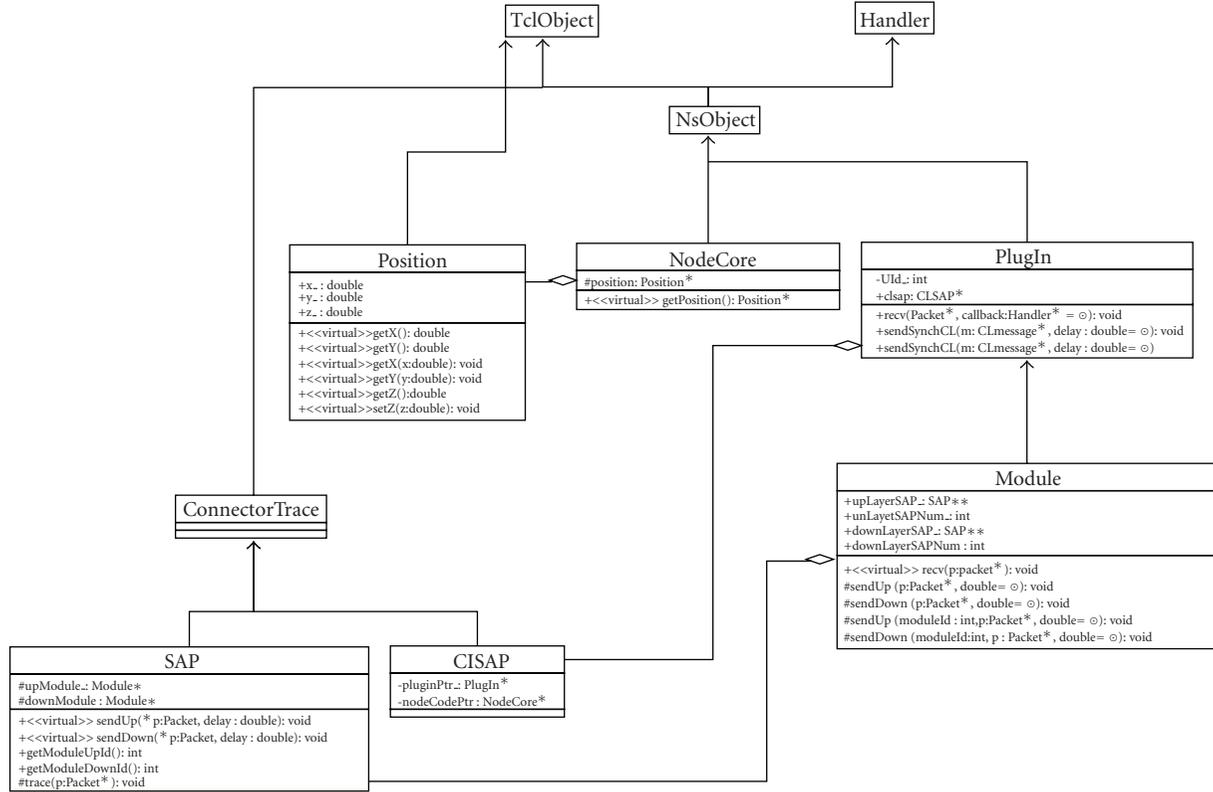


FIGURE 2: Class diagram for the Miracle framework.

An overview of the most important classes in Miracle and their relationship is represented in Figure 2. A complete guide on how to use Miracle (e.g., how to create a simulation script, or how to write a module with cross-layer capabilities) is beyond the scope of this paper. We note, however, that as a part of the development and maintenance of Miracle, several user guides and tutorials have been written, most of which are listed at the official Miracle web page [14]. Furthermore, the current Miracle maintainers also run a mailing list named `nsmiracle-users` (whose information is also reported in [14]) to which Miracle users can refer in case they encounter any problem which is not addressed in the guides and tutorials just mentioned.

**2.3. Porting ns2 Modules in Miracle.** Special care was taken, in the design of our architecture, so as to facilitate the porting of existing ns2 code. In particular, we defined the `Module` class as a child of the `NsObject` class, as depicted in Figure 2. Hence, we can encapsulate ns2 modules within the Miracle `Module` class. This requires redirecting the input and the output of the original ns2 modules to the `Module` class, which is now in charge of connecting the original module with the rest of the protocol stack. This allows the reuse of existing ns2 code. However, in this case modifications to the original ns2 modules amount to rewriting part of the original module and recompiling the entire ns2 distribution in order to make the changes effective. To solve this problem, we can

alternatively copy the code of the original ns2 module in the extension of the related Miracle `Module` class. In this case, the code becomes independent of the ns2 distribution, and can be modified and recompiled separately (in most practical cases, it will be built either as part of Miracle or as a separate dynamic library).

**2.4. Miracle Distribution and Development.** Code and documentation related to Miracle can be found at the following link [14]. We recently put the Miracle code in a repository hosted at the Department of Information Engineering (DEI) of the University of Padova; the procedure for connecting to the repository is described in [14]. One of the key features offered by the new repository is that we can provide access to people outside this institution. This is a significant change, since it means that the development of Miracle will be from now on much more open to the community. Users, in order to have access to advanced functionalities, may want to work with the latest version of the code stored in the repository, instead of the latest stable release. This of course comes at the cost of some degree of instability of the code. This repository is freely accessible in read-only mode, while write access can be requested by interested contributors.

### 3. Miracle PHY and MAC

**3.1. Related Work.** Accurate channel and PHY layer modeling has drawn a significant amount of attention in recent

years, and much work has been done in this respect. The ns2 simulator, in particular, was well known for its poor channel and PHY layer modeling, and for this reason several enhancements have been proposed [15–17]. However, the addition of this functionality has always been done in a technology-specific manner, and often in a “quick-and-dirty” fashion. The ns2 mobile node, in particular, does not have a good separation of functionalities between the MAC and the physical layer [16]. As an example, some key PHY functionalities, such as in particular the determination of the end of the reception of a packet, are performed at the MAC layer, making it difficult to introduce functionalities such as interference calculation, as well as making the code notoriously hard to read and to debug. In fact, the introduction of features such as enhanced error and interference models has required significant modifications, such as those introduced in `dei80211mr` [15], and improving the architecture of the code for the sake of easier debugging and readability has required its complete redesign, as is the case of the new IEEE 802.11 model of [16]. Moreover, the introduction of the support for new wireless technologies has required extensive tweaking, if not even the use of the ns2 code as a mere entry point for completely customized code, as is the case of [18]. To summarize, every time a new technology is to be implemented, significant developer effort is needed, which is exacerbated by the fact that the basic ns2 mobile node does not provide good channel models, and that all extensions in this respect have been too much technology-specific and cannot be easily reused for different technologies. Regarding other simulators, it is to be noted that some of them, such as ns3, allow the specification of customized callbacks between modules at different layers of the protocol stack. However, the type of interactions in use commonly varies depending on the technology being considered as well as on the particular implementation, and a well-defined set of callbacks to be exploited for channel, PHY and MAC layer modeling is still lacking. Finally, to the best of our knowledge, no well-known simulator provides a good and generic model addressing how different wireless technologies make use of the frequency spectrum and mutually interact.

**3.2. The Miracle PHY and MAC Framework.** The Miracle PHY and MAC framework was explicitly designed to overcome these issues. In our effort to develop a modular and extensible framework for channel and PHY layer modeling, we chose an object-oriented design and we defined a set of classes, as shown in Figure 3.

The channel model we developed is based on the modeling of a fundamental entity, the PHY Layer Transmission (PLT) of a packet. We define a PLT by the attributes characterizing it; choosing these attributes corresponds to choosing our PHY and channel modeling assumptions. PLTs instances have a 1 : 1 association with ns2 Packet instances, and therefore PLT attributes are conveniently gathered in a new ns2 packet header named `hdr_MPhy`. The attributes we define for PLTs, and the consequent channel modeling assumptions we make, are as follows:

(i) **duration:** a PLT is an event which extends over a given time interval. The length of this interval is given by the `duration` attribute.

(ii) **Pt:** a PLT is characterized by its transmission power, as set by the PHY layer of the transmitter. This attribute refers to the PLT as a whole; in other words, power is considered to be constant during the whole duration of a transmission. This choice is intended to achieve a reasonable tradeoff between modeling accuracy and complexity. We note that, while this is the approach in use by the vast majority of simulators, it is nevertheless a simplifying assumption of which we should be aware.

(iii) **Pr:** the processes performed on the reception of a PLT are modeled by mathematical operations performed on the `Pt` attribute, which result in the `Pr` attribute, that represents the received power. Examples of these processes are propagation effects, antenna gains, RF filtering, and signal processing at the PHY layer (e.g., interleaving, coding, etc.).

(iv) **Position:** a PLT is characterized by the geographical position of the transmitter (`srcPosition`) and that of the receiver (`dstPosition`). These attributes are references to instances of classes belonging to the `Position` class hierarchy defined in Miracle, which we discussed in Section 2. They can provide additional information such as the direction and the speed of motion in case the nodes are mobile. This can be used for enhanced channel modeling features, such as the determination of the effects of fast fading as a function of speed.

(v) **modulationType:** this is a value univocally identifying the particular modulation and coding scheme in use by the physical layer. The main purpose of this attribute is to provide support for modeling the acquisition process in multi-technology scenarios (by *acquisition process* here we mean the set of tasks such as preamble detection, which are commonly performed by the PHY layer at the beginning of a reception). We note that this solution can accommodate perfect acquisition models, where the receiver always correctly acquires signals of the desired type and discards all others, as well as more complex solutions such as stochastic models for preamble detection.

(vi) **srcSpectralMask:** a transmission consists of power radiated nonuniformly into the frequency spectrum. We assume that the specification of the power spectral density function of the transmission (normalized with respect to the transmission power) can account in sufficient detail for this fact. `srcSpectralMask` is a pointer to a class of the `MSpectralMask` hierarchy which is intended to implement this function. We chose to use an abstract class for this purpose, in order not to pose any particular limitation on how this function is implemented. Nevertheless, piece-wise constant or linear functions should be enough for most purposes, and for this reason the only implementations we provide for `MSpectralMask` use a rectangular function.

(vii) **dstSpectralMask:** each reception process is characterized by an RF filter, which is represented by means of its frequency response. The implementation issues for this are the same as for the spectrum usage information discussed above. For these reasons, as we did for the power spectral

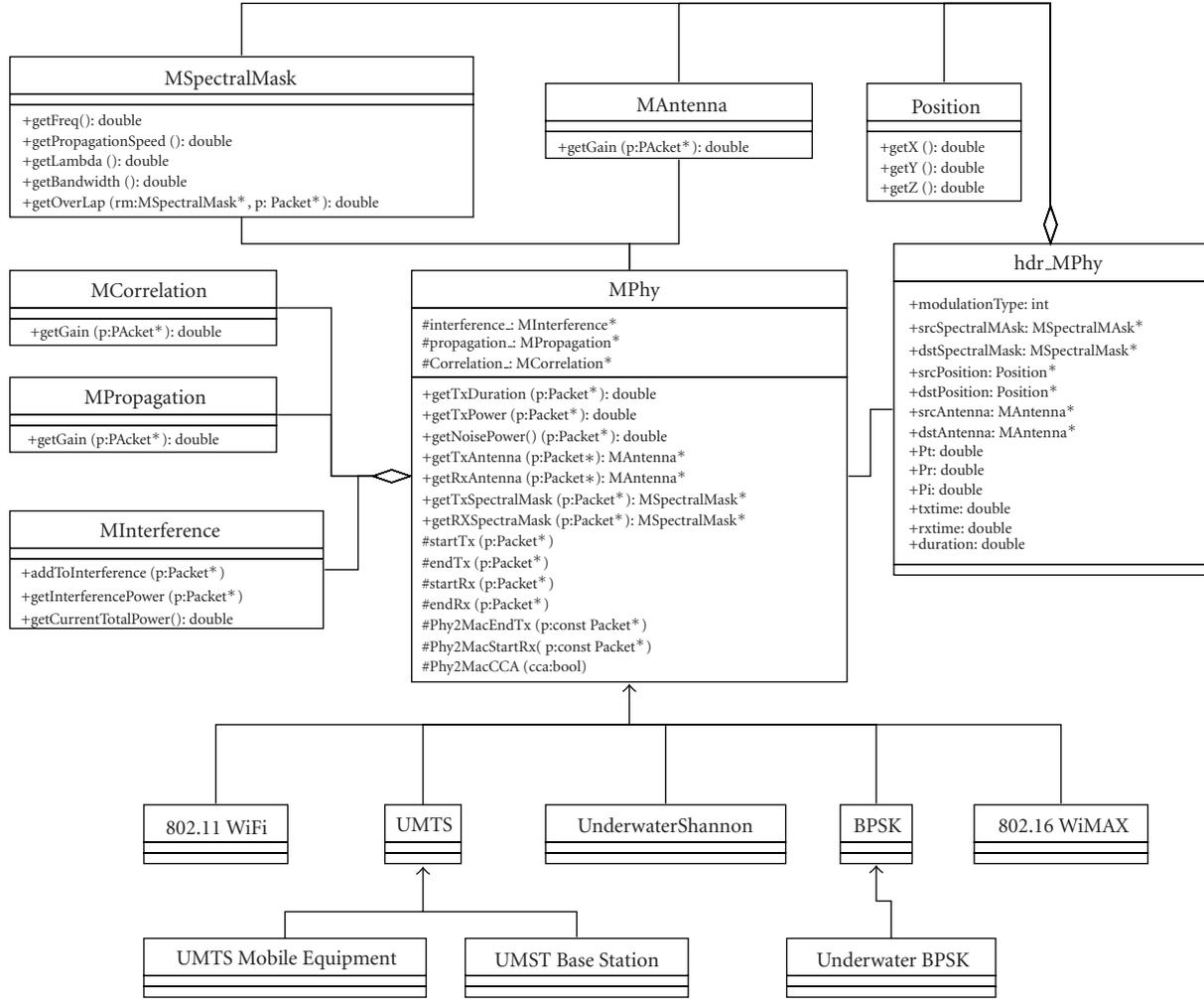


FIGURE 3: Class diagram for MPhy and related classes.

density of PLTs, RF filters are represented by instances of the `MSpectralMask` class. The RF filtering process is modeled as a gain applied to the received power of the PLT; this gain is determined as a function of the spectral mask applied to the transmission and the carrier frequency.

(viii)  $P_n$ : the noise power at the receiver. The value of this attribute is calculated by the receiving `MPhy` instance in a technology-dependent fashion. For most wireless technologies, we argue that it will suffice to determine the noise power according to an AWGN model by integrating a predetermined noise spectral power density over the frequency response of the RF filter (which is implemented by `dstSpectralMask`). We note that for some particular models, such as the underwater acoustic communications model that we will describe in Section 4.3, more complex calculations need to be involved.

(ix)  $P_i$ : the multiuser interference is summarized by the interference power attribute  $P_i$ , calculated aggregating all simultaneous PLTs (whose transmissions overlap in time), and with respect to a particular PLT for which reception is being attempted. We do not pose any particular

constraint on the exact model to be used for this purpose. Rather, interference models are to be implemented by inheriting from the `MInterference`, and implementing the `addToInterference()` and `getInterferencePower()` methods according to the chosen model. We provide one particular implementation of these classes, called `InterferenceMIV`, which aggregates all simultaneous PLTs (also referred to as interfering PLTs) into a single piece-wise constant function of time using the well-known Gaussian model (i.e., summing power values), and returns the total interference power on a given packet calculated as the mean integral value of the aggregation of interfering PLTs.

The other important element of our channel and PHY modeling framework is the `MPhy` class: it is an abstract class providing channel modeling functionalities and the API for the development of PHY layer implementations. Channel modeling is implemented by associating each `MPhy` instance with instances of other objects which implement the different components of a channel model. We define the following classes of objects for channel modeling:

- (i) `MPropagation`: similarly to the `Propagation` class of `ns2`, implementations of this class account for the attenuation of the power of a PLT due to effects such as path loss, fading, and shadowing;
- (ii) `MAntenna`: similarly to the `Antenna` class in `ns2`, this class hierarchy provides means to implement the gain of directional antennas as a function of PLT attributes (the most useful for this purpose being the position attributes);
- (iii) `MCorrelation`: this class of objects is intended to implement the gains due to the signal processing performed by the receiver. A remarkable use case for this class of objects is the processing gain of direct sequence spread spectrum (DSSS) and code division multiple access (CDMA) systems.
- (iv) `MInterference`: this class of objects handles the calculations of multi-user interference.

The first three of the above mentioned classes are only required to implement a `getGain(Packet* p)` method which is expected to provide the gain value to be applied to a given PLT. On the other hand, the `MInterference` class is required to produce the interference perceived by a particular PLT. This task is more complex since in general interference depends on all PLTs whose transmission overlaps in time and frequency with the particular PLT being considered (target PLT). For this reason, classes implementing `MInterference` are expected to keep track of all currently active PLTs (i.e., whose transmission is ongoing), by providing implementation of two methods: `addToInterference(Packet* p)`, which has to be called at the beginning of the transmission of every PLT so it can be added to the set of active PLTs, and `getInterferencePower(Packet* p)`, which returns the interference caused by all active PLTs on the target PLT.

The `MPhy` class is meant to only provide support for functionalities which are shared by different channel models and wireless technology implementations. Technology-specific PHY layer functionalities are taken into account by inheriting from the `MPhy` class and implementing the following virtual methods:

- (i) `getTxDuration(Packet* p)`: must be provided by the transmitting PHY to determine the duration of a transmission.
- (ii) `getTxPower(Packet* p)`: must be provided by the transmitting PHY to determine the transmission power to be used for a given PLT.
- (iii) `getNoisePower(Packet* p)`: must be provided by the receiving PHY to determine the noise power at the receiver for a given PLT.
- (iv) `getTxAntenna(Packet* p)` and `getRxAntenna(Packet* p)`: must be provided by, respectively, the transmitting and receiving PHYs to determine the antenna being used for a given PLT.
- (v) `getTxSpectralMask(Packet* p)`: must be provided by the transmitting PHY to determine the spectrum used by a PLT.

- (vi) `getRxSpectralMask(Packet* p)`: must be provided by the receiving PHY to determine the RF filter used for receiving a PLT.
- (vii) `getModulationId(Packet* p)`: must be provided by the transmitting PHY to determine the modulation and coding scheme to be used for a PLT.
- (viii) `startTx(Packet* p)`: the entry point for the code that is to be executed at the beginning of a transmission. The implementation of this method is responsible for actually sending the `Packet` instance on the channel.
- (ix) `endTx(Packet* p)`: the entry point for the code that is to be executed at the end of a transmission.
- (x) `startRx(Packet* p)`: the entry point for the code that is to be executed at the beginning of a reception. This code should handle the PLT acquisition process, for example, implementing preamble detection, synchronization, and so forth.
- (xi) `endRx(Packet* p)`: the entry point for the code that is to be executed at the end of a reception. This code is responsible for determining the presence of errors in the packet, using an error model suitable for the PHY technology being implemented, and for the eventual forwarding of the `Packet` instance to the upper layers.

One of the reasons for which we developed APIs for PHY and MAC layer development is that the `ns2 MobileNode` did not natively provide support to simulate the different phases of transmission and reception of packets, neither at the MAC nor at the PHY layer. A diagram of this is shown in Figure 4: at the transmitter, only the beginning of a transmission is considered, both at the MAC and PHY layers; at the receiver, the PHY layer is only aware of the beginning of the reception, while the MAC layer has notion of both the beginning and the end of the reception. This in our opinion is not a good design. First of all, whenever the MAC and the PHY layers need to perform any operation upon packet termination (i.e., change the status of the PHY or the MAC state machine), dedicated events need to be generated. Secondly, the duration of a transmission is determined at the PHY layer, since it depends on the packet size, the modulation and coding scheme, and possibly other PHY-specific aspects such as the length of synchronization preambles; consequently, having to determine it at the MAC layer to schedule the necessary events involves the duplication at the MAC layer of PHY layer attributes and functionalities, which can lead to inconsistencies and poor readability and maintainability of the code. Finally, this design has led to the misplacement of the implementation of several functionalities; for example, this is the case of PHY error models, which in several implementations had to be placed within the `recv_timer()` method of the MAC code.

Our design, represented in Figure 5, attempts to solve these issues. First of all, the duration of a PLT is always determined by the PHY layer; furthermore, the scheduling of the start/end of transmission and reception events is a functionality provided by the `MPhy` base class, which takes care of

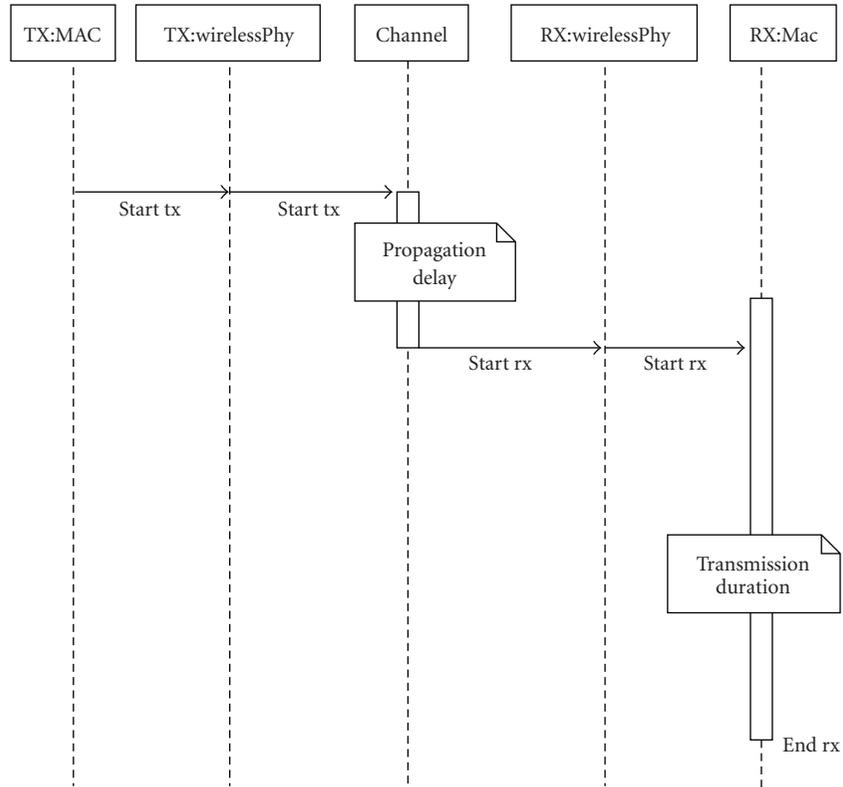


FIGURE 4: Sequence diagrams for packet TX/RX events in the ns2 MobileNode.

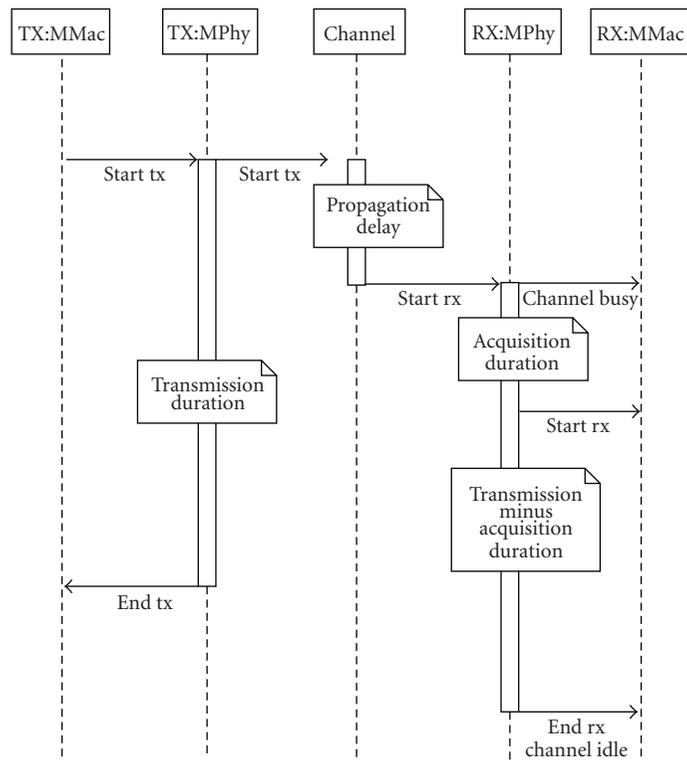


FIGURE 5: Sequence diagrams for packet TX/RX events in the Miracle Phy and Mac framework.

calling the entry points for the technology-specific PHY layer code. Third, a set of cross-layer messages (a functionality natively provided by the Miracle framework) is defined so that MPhy-derived classes can trigger the transmission/reception start/end events on the MAC layer. Finally, the base MMac class defines some methods (`Phy2MacEndTx()`, `Phy2MacStartRx()`, and `Phy2MacEndRx()`) which are called upon reception of the above mentioned messages, and can therefore be used by classes inheriting from MMac to implement protocol-specific code which needs to be executed in response to the corresponding events. We note that our design is significantly closer than that of the `MobileNode` to the way in which real devices operate, for the same reasons which are discussed in [16] for the particular case of IEEE 802.11.

#### 4. Wireless Technologies Implemented in Miracle

Several types of wireless technologies have been implemented using the Miracle PHY and MAC framework. A first set of modules implements very generic technology such as a BPSK-based PHY layer and an ALOHA-based MAC; these modules were developed mainly as a proof of concept and for debug purposes, but still the fact that they have been implemented using the Miracle PHY and MAC framework provides them with features that, while rather trivial, could not have been easily implemented in other network simulators. For instance, the fact that the communication rate provided by the BPSK PHY is proportional to the spectrum that is assigned to it, and that the ALOHA MAC adapts its transmission rate to the communication rate of the underlying PHY without having to know how it is calculated, just by receiving a notification upon the end of the packet transmission. A second set of modules provides implementations of more realistic wireless technologies. In this set we include modules for standard radio technologies such as IEEE 802.11, UMTS, and WiMAX, as well as models for the realistic simulation of Underwater Acoustic Networks. In the remainder of this section, we will describe these modules in detail.

*4.1. dei80211mr.* IEEE 802.11 support in Miracle is provided by `dei80211mr`, which was originally conceived as an enhancement of the original `ns2` implementation of IEEE 802.11. As such, it does not only work with Miracle, but also with plain `ns2`. `dei80211mr` provides the following features:

- (i) support for multiple transmission rates, modulation and coding schemes as defined in the IEEE802.11b/g standards. This includes support for rate adaptation, that is, for dynamically switching at runtime the modulation and coding scheme used;
- (ii) a realistic interference model which calculates the signal to interference plus noise ratio (SINR) for each connection by considering all packets in flight. The packet error rate is determined as a function of SINR according to packet error rate curves. These for IEEE

802.11g are obtained off-line by means of a dedicated OFDM physical layer simulator. For IEEE802.11b, we instead used an analytical model of the direct sequence spread spectrum (DSSS) technique. Note that the SINR-based packet error model provides a capture model which is more realistic with respect to the one adopted by `ns2`, which relies on a predetermined capture power threshold.

- (iii) several well-known bugs present in the original `ns2` 802.11 model [19] were fixed, in particular the ones regarding “Direct Access Denial”, “Random Backoff Time”, and “Capture Model” (we note that “Capture Model” in [19] actually refers to a synchronization issue, which therefore differs from the capture model issue we discussed earlier in this section).

Furthermore, an extended version of `dei80211mr` has been developed which achieves a tighter integration with Miracle by porting all the traditional PHY and MAC codes to the MPhy/MMac architecture. In doing this, it was possible to introduce additional features, such as the following.

(i) An improved code architecture. As discussed in [16], the code of the original `ns2` IEEE 802.11 model is the result of years of incremental development, and for this reason it does not have a clear and well-defined architecture, but rather it is very complicated and difficult to understand and modify without causing undesired side effects. The first releases of `dei80211mr`, in spite of the new features they introduced, largely shared that garbled code architecture, together with its problems. The porting of `dei80211mr` to the MPhy/MMac framework, thanks to its well-designed API, made it possible to restructure the code of `dei80211mr` to yield a clearer architecture with a more meaningful split of functionalities among PHY and MAC layers.

(ii) Enhanced Clear Channel Assessment (CCA) model. The IEEE 802.11 standard specifies that three different methods can be used for CCA: (1) energy Detection (ED), (2) preamble detection, (3) a combination of the former two. Most IEEE 802.11 simulation modules, including the old `ns2` model and the current official `ns3` WiFi stack, only implement ED. The MPhy-enabled `dei80211mr` exploits the Carrier Sense functionality of the MPhy/MMac interface to implement all three CCA methods defined by the standard.

(iii) Support for Adjacent Channel Interference calculation. The IEEE 802.11 standard for the 2.4 GHz band specifies the use of a number of channels (11 in the US, 13 in Europe) which are 20 MHz wide and whose central frequencies are separated by 5 MHz. As a result, nearby channels overlap in frequency, and wireless devices operating in nearby channels experience the so-called Adjacent Channel Interference (ACI). While traditionally it has always been considered a good practice to use only sets of orthogonal channels (e.g., channels 1, 6, and 11) for frequency assignment in IEEE 802.11 deployments, recent research showed that, in some scenarios, the use of partially overlapped channels can increase the capacity of wireless networks [20, 21]. Most network simulators, unfortunately, do not provide means for simulating these scenarios. On the other hand, thanks to the spectrum-awareness of the MPhy

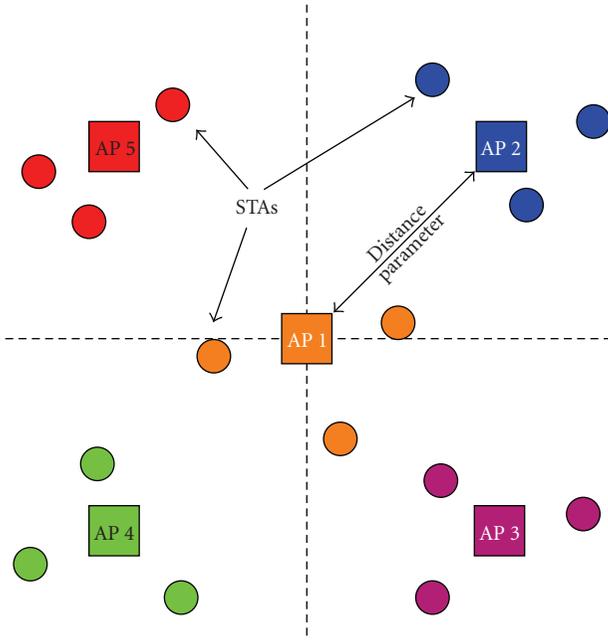


FIGURE 6: Topology for adjacent channel interference scenarios.

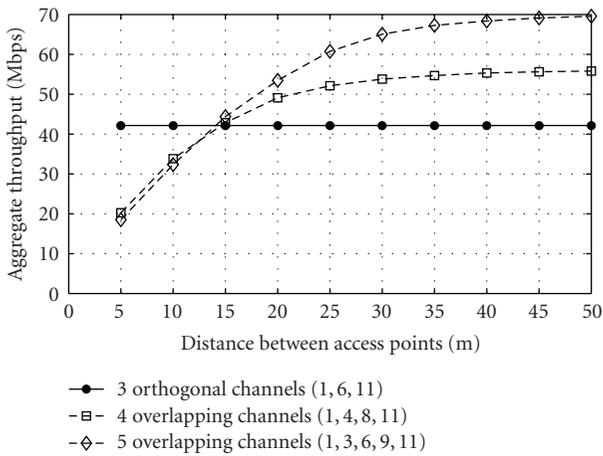


FIGURE 7: Performance in adjacent channel interference scenarios.

framework, it is possible to simulate WiFi scenarios with Adjacent Channel Interference using `dei80211mr`.

As an example study, we used the MPhy-enabled version of `dei80211mr` to obtain the performance of the scenario represented in Figure 6 for different choices of the set of channels to be allocated to the access points (APs); a detailed description of the simulation setup, as well as a more comprehensive set of results, can be found in [22]. The results of Figure 7 show that when the distance between APs is greater than a given threshold, the use of partially overlapping channels is effective in enhancing the capacity of the network; on the other hand, when the APs are close to each other, the effects of adjacent channel interference prevail, and it is therefore more convenient to use orthogonal channels.

4.2. *UMTS*. The UMTS library was developed starting from MPhy (see Section 3.2) and the *eurane* extension for ns2 [23]. *eurane* focused mostly on the implementation of the UMTS RLC protocols and of the UMTS access network architecture, but used a rather simplistic model for the PHY layer. Thanks to MPhy, it was possible to implement a much more accurate PHY model for UMTS Release 4. In particular, we used the Correlation model to account for the processing gain of CDMA; this allowed us to effectively model the interuser interference and, in turn, the soft capacity of CDMA networks. Other features offered by the Miracle UMTS library are the accurate implementation of the uplink and downlink physical control channels and data channels, including inner loop power control, and the full configurability of user scrambling codes in accordance with the UMTS Release 4 standard. As to the channel modeling, SINR measurements are translated into packet errors using suitable approximations, which we calculated off-line (similar to the fittings in [24]). This increases the simulation speed while preserving the required accuracy. Regarding radio link control (RLC) features, we ported the acknowledged mode (AM) RLC from *eurane*, which implements packet fragmentation, selective repeat ARQ (with a bitmap acknowledged mode), and data concatenation. We added the SDU discard functionality in order to avoid infinite retransmission loops (as is often done in practical systems). An example of a typical UMTS architecture which can be simulated with the Miracle UMTS module is depicted in Figure 8.

4.3. *Underwater Acoustic Communications*. The underwater library deeply relies on the MPhy framework (see Section 3.2) to deal with multi-user interference, propagation gain, channel delay, and noise power. The library comes in two flavors:

- (1) a simplified version uses empirical equations for the calculation of delay, attenuation, and noise power. These equations can be found in [25, 26];
- (2) a more powerful configuration called World Ocean Simulation System (WOSS) [27]. Actual propagation theories [28] aim to model channel power delay or frequency attenuation profiles. WOSS is a multi-threaded framework that permits the integration into Miracle of any existing underwater channel simulator that expects environmental data as input and that provides as output a channel realization represented using the channel profiles just mentioned. Currently, WOSS integrates the Bellhop ray-tracing program [29] while retaining the previous formula for the noise power.

In both cases, the propagation effects are considered *constant over the duration of the packet*. Specifically, Bellhop calculations are performed across the whole bandwidth with custom resolution, while noise calculations are performed at the geometric frequency (let  $f_l$  and  $f_u$  be, respectively, the lower and upper limits of the frequency band, then the geometric frequency is  $\sqrt{f_l f_u}$  [30]). To calculate the solution

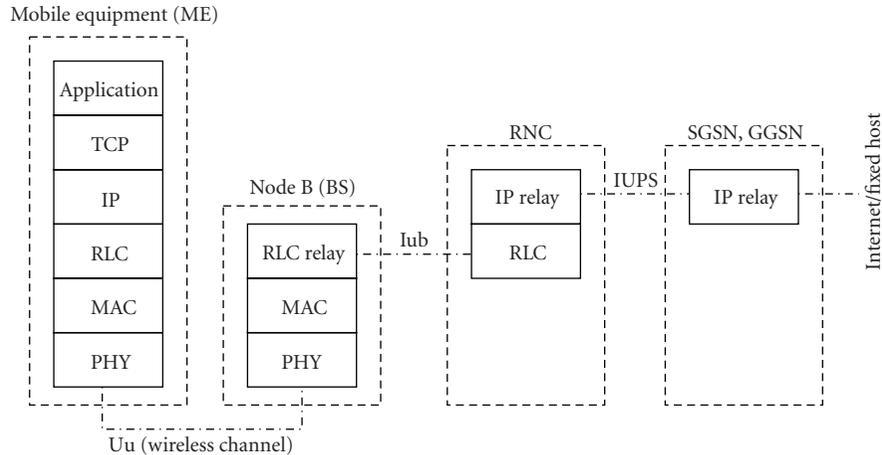


FIGURE 8: Example architecture which can be simulated with the Miracle UMTS module. ME is the mobile user, Node B is the UMTS base station (BS), RLC is the radio link control (hosting ARQ algorithms), RNC is the Radio Network Controller (in charge of connection handling, handovers, QoS control, call admission control, etc.), SGSN and GGSN are, respectively, the serving and gateway GPRS support nodes.

of the propagation equations between a transmitter and a receiver, Bellhop requires the knowledge of the Sound Speed Profile (SSP), the Bathymetric Profile (BP), and the type of Bottom Sediments (BS), required to model acoustic power losses from bottom reflections. The *Sound Speed Profile* is the propagation speed of sound considered as a function of water depth. Different profiles lead to potentially very different propagation effects, including surface sound channels, deep sound channels, convergence zones, shadow zones, and so on; see [28]. In this respect, WOSS offers a technology independent database API and a number of classes to manipulate SSP, BP, and BS data. For the SSP, we employ a custom implementation of the World Ocean Database [31], a collection of SSPs measured during a number of experiments all around the world; the measurements are divided by location and day or season of the year when the measurement was performed (recall that sound propagation is affected by water temperature, which in turn undergoes seasonal changes, especially in the superficial layer). The bathymetric data have been taken from the General Bathymetric Chart of the Oceans [32], a public database offering samples of the depth of the sea bottom with an angular spacing of 30 seconds of arc. Finally, the type of bottom sediments is provided by a reasoned geo-acoustic analysis of the National Geophysical Data Center's Deck41 data-base [33]. The effort of interfacing all components pays off, in that the user only has to specify the location in the world and the time where the simulation should take place. This is done by setting the simulated date and the wanted latitude and longitude of every node involved. The simulator automatically handles the rest. In more detail, the simulator picks the location (i.e., latitude, longitude, and depth) of the transmitter and the receiver and queries the database manager for samples of bottom sediments, measured SSPs (for simplicity, the SSP can also be assumed to be constant, on average, throughout the network area) and for bathymetric data along the path. Full customization of "surficial", bathymetric and SSP data

is also possible if more accurate data is available (with the term "surficial" we refer to the surface of the sea bottom, as opposed to superficial, which usually refers to the water surface). The power delay profile obtained with Bellhop can be used to schedule the reception of replicas of the packet: in detail the user can choose to coherently combine the complex channel gains with a custom resolution time window and obtain one or more complex channel taps.

In Figures 9 and 10, we show the coherent sum of all channel taps, obtained with WOSS for an example scenario. Figure 9 represents the attenuation incurred by an acoustic wave at 4 kHz transmitted in August, approximately 20 km offshore the harbor of Taranto, Italy, with the transmitter located at 40.32°N, 17.12°E. Darker shades of gray represent stronger signal power. The figure shows that the signal reaches the surface near the harbor (top right corner, about 11 km from the transmitter) bearing sufficient power to allow correct reception. By contrast, Figure 10 shows the same scenario in March: in this case, the average temperature of the water is lower, changing the way the sound is refracted and reflected by the sea bottom. Here, any acoustic receiver deployed between 9 and 11 km from the transmitter may be unable to acquire the transmitted signal. Furthermore, a shadow zone of about 2 km appears in front of the transmitter, causing failure in a hypothetical short range communication scenario.

**4.4. WiMAX.** WiMAX [34, 35] is a standard defined by IEEE802.16 task group for wireless broadband access networks, designed to provide high-speed wireless access. Several extensions of ns2 providing WiMAX support have been proposed in the last few years; one of the most popular is that implemented by the NIST laboratories [36]. This work has been subsequently adapted to Miracle by the DISCO group of the University of Karlstad [37]; this version provides more accurate modeling of a Time Division Duplexing (TDD)

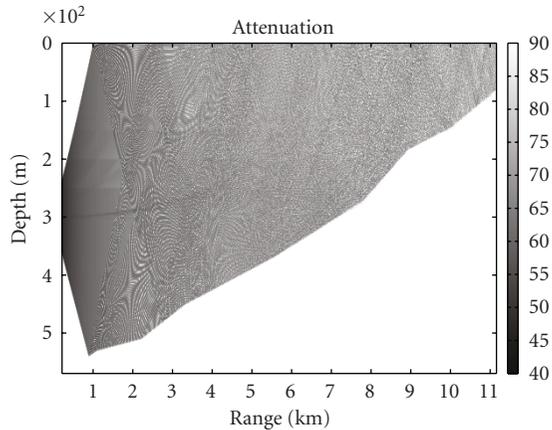


FIGURE 9: Attenuation incurred by acoustic waves at 4 kHz transmitted in August approximately 20 km offshore Taranto harbor, 40.32°N, 17.12°E. A darker shade of grey represents a stronger signal. Surficial sediments are a mixture of sand and clay; a sharply increasing sea bottom profile can be seen in the lower half of the picture.

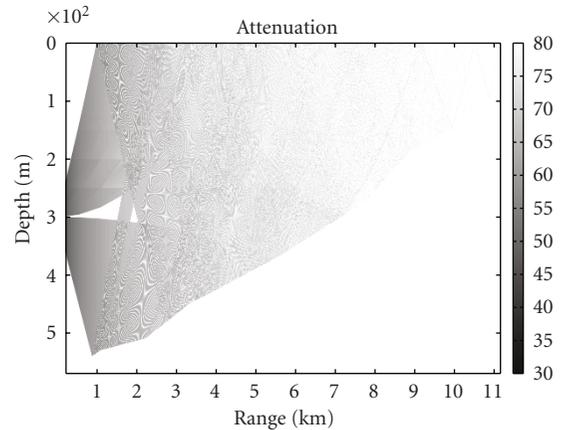


FIGURE 10: Attenuation incurred by acoustic waves at 4 kHz transmitted in March approximately 20 km offshore Taranto harbor, 40.32°N, 17.12°E. A darker shade of grey represents a stronger signal. The figure refers to the same geographical area of Figure 9.

Orthogonal Frequency Division Multiplexing (OFDM) system, together with additional functionalities such as network entry, flow management, scheduling and mobility extension. In order to extend this WiMAX module for Miracle, several enhancements have been developed during the Democles project [38] resulting in a new library called WiMAX for Democles (WiDe) [39], as we discuss in the following.

First of all, our work focused on providing a more accurate model of the PHY layer. Previously, the WiMAX Miracle module relied on a simple disk propagation model, where the packet reception behavior was determined by simply comparing the received power with a predetermined threshold, equal for all transmission schemes. This assumption is too simplistic, since the different modulation and coding schemes which can be used in WiMAX offer a range of different tradeoffs between transmission speed and reliability. Moreover, the physical transmission of OFDM systems such as WiMAX is affected by complex propagation phenomena due to the time and frequency selective nature of the channel. What happens is that the different subcarriers (from 256 up to 2048 in WiMAX) in which the available bandwidth is subdivided may experience frequency selective fading, in which case they are affected by different channel gains. In order to address these aspects, we introduced the possibility of simulating the effect of propagation (i.e., path loss, shadowing, and fading components) for each of the subcarriers. This allows the calculation of signal-to-interference plus noise ratios (SINR) for each channel, which are ultimately used to compute packet error probabilities (PER). The mapping SINRs  $\rightarrow$  PERs is done through curves obtained off-line using a link level simulator. These curves were mapped using the Mutual Information Effective SINR Mapping technique (MIESM) [40], according to the methodology described in [41]. We adopted this approach to extend the OFDM module of the NIST code and to design a new PHY layer module supporting the Orthogonal

Frequency Division Multiple Access (OFDMA) technology, which is adopted by mobile WiMAX. The implemented subchannelization scheme is the Partial Usage of the Sub-Channels (PUSC) where the 1024 subcarriers are mapped to 30 logical nonadjacent channels so as to improve the independence of the channel response across subcarriers.

From a data link layer perspective, we added support for Automatic Repeat reQuest (ARQ) and for the relay architecture detailed in the IEEE802.16j [42] standard. The latter is an extension to WiMAX systems according to which Relay Stations (RS) are deployed in order to expand the coverage and possibly improve the throughput of the WiMAX access network. In this extension of the Miracle WiMAX module, we considered the case of nontransparent RSs, which implies that relay nodes are in charge of generating their own MAC signaling and of autonomously managing the connection with both base stations and mobile terminals.

Finally, WiDe supports the simulation of the WiMAX network reference model defined by the WiMAX Forum [43]. This model is composed by three main components: the mobile station (MS), the network access provider (NAP), and the network service provider (NSP). The MS corresponds to the subscriber station (SS) in the IEEE standard nomenclature. The NAP is composed by the set of entities that are needed to provide and manage a link layer connection with the SSs, therefore it can be composed of a single base station (BS) or a set of them. The NSP is the entity in charge of managing the incoming connectivity requests and negotiating the service requirements. A sketch of a possible architecture is given in Figure 11.

## 5. Projects Using Miracle

As a final note, we would like to mention here some research projects that used or are using Miracle.

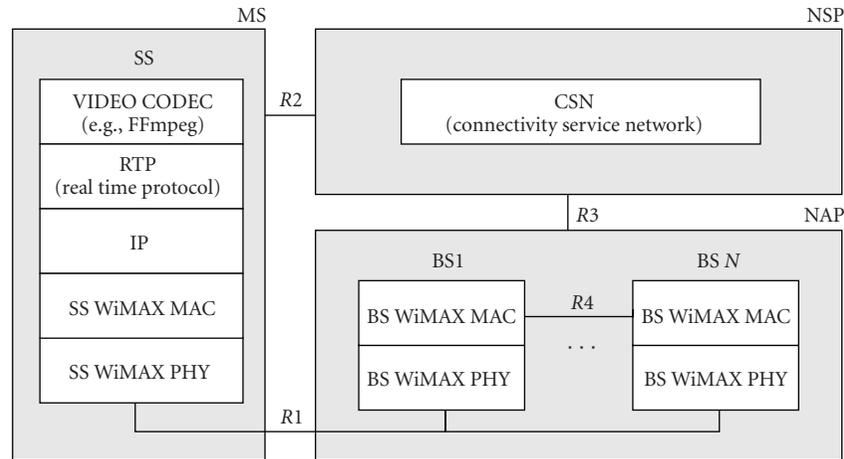


FIGURE 11: Example architecture which can be simulated with the WiDe module. Mobile station is what has been called subscriber station (SS) from IEEE standard nomenclature, the network access provider (NAP) is composed by the set of functionalities to manage a connection from radio point of view with the SSs (therefore can be a single BS or a set of them) and the network service provider (NSP) is the entity in charge of managing the incoming requests of connectivity and negotiating the service requirements.

- (i) The Ambient Networks Phase2 project [44] targeted transparent wireless access and services in a multi-technology environment. One of its main objectives was to provide support for multi-technology terminals, that is, to allow users to seamlessly migrate between different technologies and networks and, in addition, to dynamically manage the business relations with their access providers. Many research activities have been carried out using Miracle in order to test the proposed architecture.
- (ii) The ARAGORN project [45] explores key enabling technologies that facilitate the application of machine intelligence and adaptive communications technologies in the optimization of resource usage in wireless networks. Part of the research activity carried out within ARAGORN is being performed using Miracle.
- (iii) NURC [46] is one of three research and technology organizations of NATO. It conducts world class maritime research in support of NATO's operational and transformation requirements. The Centre has the ability to conduct maritime and undersea research from concept formulation to validation at sea with its exceptional combination of expertise and steady rotation of staff from and to the Nations. Mission evaluation, network analysis, and protocol dimensioning for underwater acoustic communications systems will be done using Miracle.
- (iv) The Democles project [38] is an internal project carried out at CTTC with the aim of developing a framework for simulating next generation wireless networks. As part of the most recent activity within this project, Miracle has been integrated with the pre-existing simulation framework, and is being actively used for several research activities.

We would like to note that many researchers have used and are using Miracle in their work, as is proved from the amount of interactions seen on the `nsmiracle-users` mailing list. Furthermore, many research publications have been reported to use Miracle for their performance evaluation; a complete list would be very long and is therefore omitted.

## 6. Conclusions

In this paper, we presented the Miracle framework, discussing its architecture, its features, and the wireless technology models it provides. We are confident that the features of Miracle, in particular its multi-interface and cross-layer capabilities, together with the possibility of simulating several different wireless technologies, make it a very effective tool for the simulation of 4G networks and beyond. Furthermore, the fact that Miracle is open-source, its community-based development model, and the modularity of its code base and its APIs make it a very good tool for research institutions and universities.

As a final note, we would like to point out that Miracle is still being actively developed, and therefore there are several interesting opportunities for future research and development activity, among which we would like to mention validation studies for the models currently included in Miracle, as well as the development of modules for the simulation of emerging wireless technologies such as LTE and Cognitive Radio.

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