Simulating LTE Cellular Systems: an Open Source Framework

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***Abstract*—LTE represents an emerging and promising technology for providing broadband ubiquitous Internet access. For this reason, several research groups are trying to optimize its performance. Unfortunately, at the present, to the best of our knowledge, no open source simulation platforms, that the scientific community can use to evaluate the performance of the entire LTE system, are freely available. The lack of a common reference simulator does not help the work of researchers and poses limitations on the comparison of results claimed by different research groups. To bridge this gap, herein, the open source framework *LTE-Sim* is presented to provide a complete performance verification of LTE networks. *LTE-Sim* has been conceived to simulate uplink and downlink scheduling strategies in multi-cell/multi-users environments taking into account user mobility, radio resource optimization, frequency reuse techniques, AMC module, and other aspects very relevant for industrial and scientific communities. The effectiveness of the proposed simulator has been tested and verified considering (i) the software scalability test which analyzes both memory and simulation time requirements; (ii) the performance evaluation of a realistic LTE network providing a comparison among well-known scheduling strategies.**

***Index Terms*—LTE, Simulation, Performance Evaluation, Modeling.**

I. List of Acronyms

AMC	Adaptive Modulation and Coding
CQI	Channel Quality Indicator
eNB	evolved NodeB
EPS	Evolved Packet System
E-UTRAN	Evolved UTRAN
EXP	Exponential PF
LTE	Long Term Evolution
MCS	Modulation and Coding Scheme
M-LWDF	Modified Largest Weighted Delay First
MME/GW	Mobility Management Entity/Gateway
OFDMA	OFDM Access
OFDM	Orthogonal Freq. Division Multiplexing
PDBC	Physical Broadcast Channel
PDCCH	Physical Downlink Control Channel
PDCP	Packet Data Control Protocol
PF	Proportional Fair
RB	Resource Block
RLC	Radio Link Control
RRC	Radio Resource Control
SC-FDMA	Single Carrier Freq. Div. Multiple Access
SINR	Signal to Interference and Noise Ratio
TTI	Transmission Time Interval
UE	User Equipment

II. Introduction

To face the ever growing demand for packet-based mobile broadband systems, the 3GPP [1] has introduced LTE (Long Term Evolution) specifications [2] as the next step of the current 3.5G cellular networks. An enhanced access network (i.e., the E-UTRAN, Evolved-UMTS Terrestrial Radio Access Network) and an evolved core network have been defined [3]. At the present, more than 20 cellular operators worldwide, representing together more than 1.8 billion of the total 3.5 billion mobile subscribers in the world, have already stated a commitment to LTE and more than 32 million LTE subscribers are foreseen by 2013 [4].

Starting from this premise, it is clear that the optimization of all LTE aspects is a topic worth of investigation for both industry and academia communities. It is important to remark that, at the present time, a complete system level simulator is not available for these communities. In fact, the most important vendors of mobile communication equipments have implemented their own simulators. Moreover, other simulators [5]-[8], developed in academia-industrial cooperations, can be purchased using a commercial license, and their source codes are not publicly available. In [9], a Matlab-based LTE simulator has been proposed, implementing a standard compliant LTE downlink physical layer with Adaptive Modulation and Coding (AMC), multiple users, MIMO transmission and scheduler. Unfortunately, albeit it is open source and freely available, it does not consider relevant aspects of LTE simulation, such as realistic applications, a complete LTE protocol stack, and multi-cell environments with uplink flows. In [10], a system level simulator for LTE networks has been proposed as a supplement of the previous one, in order to support cell planning, scheduling, and interference. However, it does not support a complete LTE protocol stack, uplink flows, and bearer management.

Since no open source simulation platforms are freely available for the community, the design of innovative optimization strategies is today seriously impaired. Moreover, the lack of a common reference simulator poses serious problems in the comparison of results presented by different research groups.

To bridge this gap, herein, we present an open source framework to simulate LTE networks, namely *LTE-Sim*, able to provide a complete performance verification of LTE systems.

LTE-Sim encompasses several aspects of LTE networks, including both the Evolved Universal Terrestrial Radio Access (E-UTRAN) and the Evolved Packet System (EPS). In particular, it supports single and multi-cell environments, QoS man-

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agement, multi-users environment, user mobility, handover procedures, and frequency reuse techniques. Three kinds of network nodes are modeled: user equipment (UE), evolved Node B (eNB), and Mobility Management Entity/Gateway (MME/GW). Several traffic generators at the application layer have been implemented and the management of data radio bearer is supported. Finally, well-known scheduling strategies (such as Proportional Fair, Modified Largest Weighted Delay First, and Exponential Proportional Fair [11]), AMC scheme, Channel Quality Indicator (CQI) feedback, frequency reuse techniques, and models for physical layer have been developed.

It is important to note that features covered by *LTE-Sim* will allow both researchers and practitioners to test enhanced techniques for improving 4G cellular networks, such as new physical functionalities, innovative network protocols and architectures, high performance scheduling strategies and so on. *LTE-Sim* is freely available under the GPLv3 license [12]. We believe that the high modularity of *LTE-Sim* will allow a convergence of efforts towards improved versions of the software enriched with more and more features. Such enhancements could cover: new versions of the standard, innovative resource management techniques, advanced handover procedures, protocol architectures, and so on.

The rest of the paper is organized as follows: Section III describes the software design, highlighting the most important simulator components. Sections IV and V describe the flows and the radio resource management, respectively. Section VI provides a performance evaluation of the proposed simulator. Finally, Section VII draws the conclusion.

III. Software Design

In order to ensure modularity, polymorphism, flexibility, and high performance, *LTE-Sim* has been written in C++, using the object-oriented paradigm, as an event-driven simulator. At the present, the software is composed by 90 classes, 220 files, and approximately 23,000 lines of code. Fig. 1 shows the UML (Unified Modeling Language) diagram of the most important classes implemented, highlighting their most important methods and variables.

There are four main components:

- the *Simulator*,
- the *NetworkManager*,
- the *FlowsManager*,
- the *FrameManager*.

For each of them, a dedicated class has been developed. When a simulation starts, only one object for each of the aforementioned components is created. Furthermore, to ensure that each of these classes will have only one instance during the simulation (with a global point of access) a singleton design pattern has been used [13].

Most important functionalities of main components of the *LTE-Sim* are reported in Tab. I.

For simplicity, from this moment on, we will use the notation *Class::Function()* to indicate a *Function ()* defined into the *Class*.

A simulation scenario is composed by several objects, modeling the main elements of an LTE system. Each of them can issue, if needed, a new event using a *Simulator::Schedule()* method, to enable a realistic interaction among nodes.

The *Calendar* sorts events in a chronological order, according to their timestamps. Events scheduling is handled by the *Simulator* class. In details, at the beginning of each simulation, the *Calendar* is populated by only three events: (i) the start of the simulation, using the *Simulator::Run()* method; (ii) the start of the *FrameManager*, using the *FrameManager::StartFrame()* method; (iii) the end of the simulation, using the *Simulator::Stop()* method. Then, the calendar will be populated by other events generated by LTE system elements which constitute the simulated scenario, e.g., *Application::CreatePacket()*, *NetworkNode::SendPacketBurst()*, *ENodeB::ResourceAllocation()*.

Three kinds of LTE network nodes have been implemented: UE, eNB, and MME/GW. They are created, destroyed, and handled by the *NetworkManager*. Each LTE network node can be a source or a destination of data flows, defined by the classical five-tuple: source and destination IP addresses, sender and receiver ports, and the transport protocol type.

LTE-Sim provides a support for radio resource allocation in a time-frequency domain. According to [14], in the time domain, radio resources are distributed every Transmission Time Interval (TTI), each one lasting 1 ms. Furthermore each TTI is composed by two time slot of 0.5 ms, corresponding to 14 OFDM symbols in the default configuration with short cyclic prefix; 10 consecutive TTIs form the LTE Frame.

In the frequency domain, instead, the whole bandwidth is divided into 180 kHz sub-channels, corresponding to 12 consecutive and equally spaced sub-carriers. As the sub-channel dimension is fixed, for different system bandwidth configurations the number of sub-channels varies accordingly.

A time/frequency radio resource spanning over one 0.5 ms time slot in the time domain and over one sub-channel in the frequency domain is called Resource Block (RB) and corresponds to the smallest radio resource that can be assigned to a UE for data transmission.

The actual implementation of the LTE frame structure is guaranteed by the *FrameManager* component. It is in charge of the correct scheduling of frames and sub-frames (i.e., TTIs) and of the synchronization of all the eNBs.

Physical (PHY) layer aspects are managed for both UEs and eNBs. In particular, a PHY object storing physical parameters and radio channel model (as proposed in [15]) is connected to each device. Here information such as the channel quality and the perceived interference level are saved. Further physical information (e.g., frequency carrier, available bandwidth, list of available RBs for both downlink and uplink, frequency reuse parameters, and so on) are stored in a bandwidth manager object.

Finally, four different traffic generators running at the application layer (trace-based, on-off, constant bit rate, and infinite buffer) have been developed.

With *LTE-Sim*, a LTE scenario can be created as a static function in a C++ header file. A reference to this function should be added into the main program (see Sec. VI-A for details about how to create a scenario).

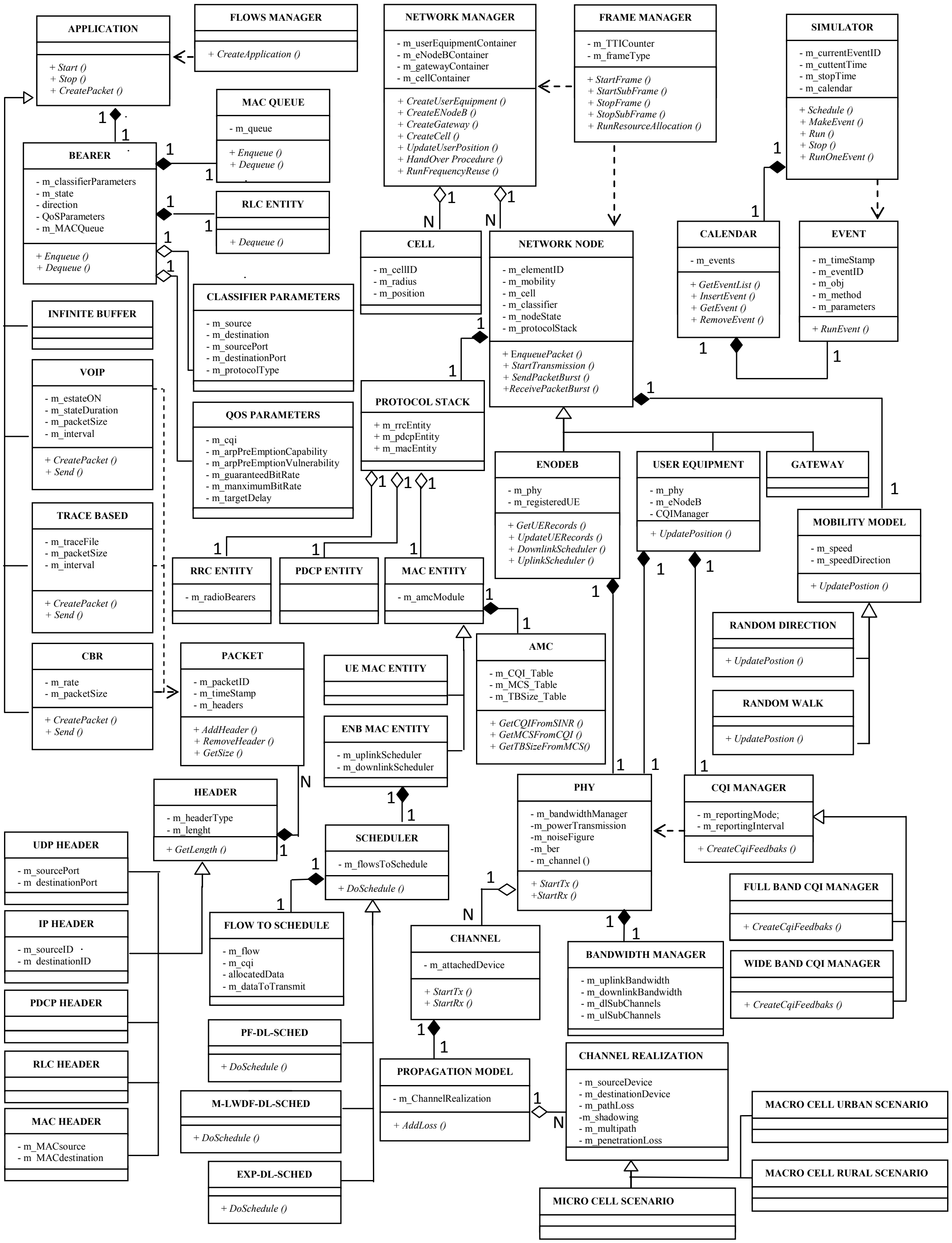


Fig. 1. The *LTE-Sim*: class diagram.

TABLE I
MAIN COMPONENTS OF THE LTE-SIM

Component	Functionalities	Important Methods	Method description
Simulator	- Creates/Handles/Ends an event	Schedule()	Creates a new event and insert it into the calendar.
		RunOneEvent()	Executes an event.
		Run() / Stop()	Starts / ends the simulation.
FrameManager	- Defines LTE frame structure - Schedules frames and sub-frames	StartFrame() and StopFrame()	Handles the start and the end of the LTE frame.
		StartSubFrame() and StopSubFrame()	Handles the start and the end of the LTE sub-frame.
FlowsManager	- Handles applications	CreateApplication()	Creates an application
NetworkManager	- Creates devices - Handles UE position - Manages the hand over - Implements frequency reuse techniques	CreateUserEquipment()	Creates an UE device
		CreateCell()	Creates a LTE Cell
		UpdateUserPosition()	Updates the UE position
		HandOverProcedure()	Handles the hand over procedure
		RunFrequecyReuse()	Implements frequency reuse techniques

A. Basic Network Topology

Both single-cell and multi-cell simulations can be run (see Figs. 2-3).

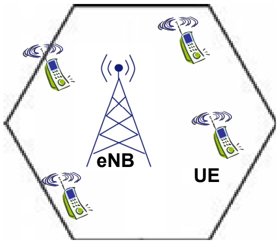


Fig. 2. Single-cell/multi-user simulation environment.

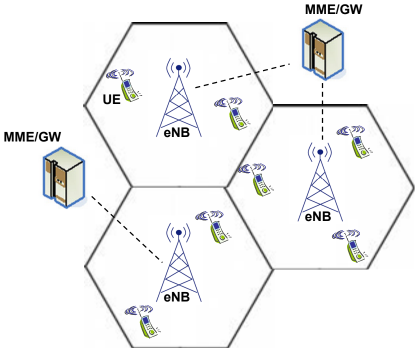


Fig. 3. Multi-cell/multi-users simulation environment.

The network topology is composed by a set of cells and network nodes (including eNBs, one or more MME/GW, and UEs), distributed among cells. All the methods for the creation and the management of the network topology are provided by the *NetworkManager* component (see Fig. 1 for details).

A LTE cell, implemented by the *Cell* class, is identified by a unique identifier (ID). Its attributes are the radius and the position defined in a Cartesian system.

For each kind of LTE network node, a dedicated class has been developed, extending the basic *NetworkNode* class (i.e., *ENodeB*, *UserEquipment*, and *MME-GW* classes). Each network node is identified by an unique ID and its position in a Cartesian system is also defined.

Support for several functionalities of both user and control plane protocol stacks is provided by the *ProtocolStack* class, developed as a container of RRC (Radio Resource Control), PDCP (Packet Data Control Protocol), and MAC entities.

The eNB performs radio resource management for the evolved radio access. Both downlink and uplink scheduling strategies are defined into its MAC entity. In particular, downlink and uplink schedulers are defined into the $m\_downlikScheduler$ and $m\_uplinkScheduler$ variables, respectively. In Sec. V, scheduling strategies that *LTE-Sim* provides are described.

As previously mentioned, for eNB and UE devices, an instance of a PHY object, namely m_phy, has been defined. PHY objects, moreover, are attached to a LTE channel, modeled by the *Channel* class. This class manages the transmission through the physical channel of the actual packet among the attached physical entities, implementing also a propagation loss model. The PHY object has been developed: for providing an interface between the LTE device and the channel; for storing and managing information about the radio channel (such as bandwidth, list of available sub-channels for both downlink and uplink); and for offering an access to the radio channel to simulate the packet transmission and reception. Further details about the implemented channel and physical models are provided in Sec. V.

CQI reporting is another important feature performed by the UE . In particular, *LTE-Sim* supports also the CQI reporting feature [16], i.e., the UE estimates channel quality and converts it in a set of CQI feedbacks reported to the eNB. Our simulator supports both periodical and aperiodical CQI reporting and both full band and wide band reporting modes. During the simulation, each eNB maintains the list of UEs associated to it, storing, for each of them, the ID and the latest CQI feedbacks. Furthermore, eNBs and UEs are aware of the LTE cell they belong to. In fact, each UE keeps up to date the ID of the cell it belongs to and the ID of the eNB it is registered to.

B. Users Mobility

In order to support user mobility, a system level intercell handover procedure has been implemented. Two types of mobility models are supported: Random Direction and Random Walk [17]. For each of them, a dedicated class has been developed, extending the basic *MobilityModel* class, i.e., *RandomDirection* and *RandomWalk* classes. In *MobilityModel* class, m_speed and $m\_speedDirection$ variables are used to define the speed and the travel direction of the user, respectively. For each UE, an $m\_mobility$ element has been created to manage mobility. According to [15], user speed should be chosen among the values 0, 3, 30, and 120 km/h, equivalent to static, pedestrian, and vehicular scenarios, respectively.

When the Random Direction model is used, the UE randomly chooses the speed direction, that remains constant during the time, and moves towards the simulation boundary area. Once the simulation boundary area is reached, the UE chooses a new speed direction.

When the Random Walk is used, the UE randomly chooses the speed direction and moves accordingly for a given travel distance that depends on the user speed. The UE changes its speed direction after covering this distance or, as in the previous model, once the simulation boundary area is reached. As default, the travel distance is equal to 200, 400, 1000 m when user speed is equal to 3, 30, and 120 km/h, respectively.

Figures 4-5 show an example of traveling pattern in a network topology composed by 19 cells with radius equal to 1 km, using both Random Direction and Random Walk mobility models. It is important to note that more sophisticated mobility models can be easily defined by extending the *MobilityModel* class.

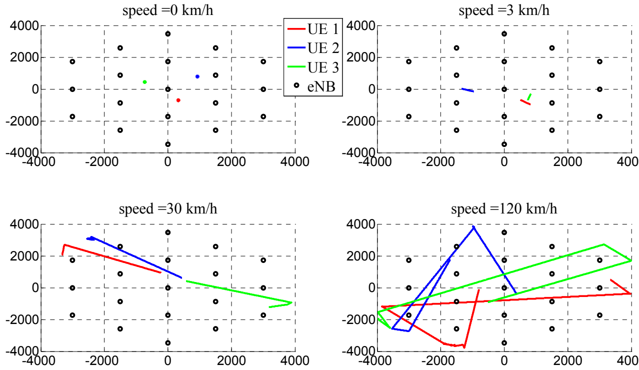


Fig. 4. Traveling pattern of UEs with the Random Direction mobility model.

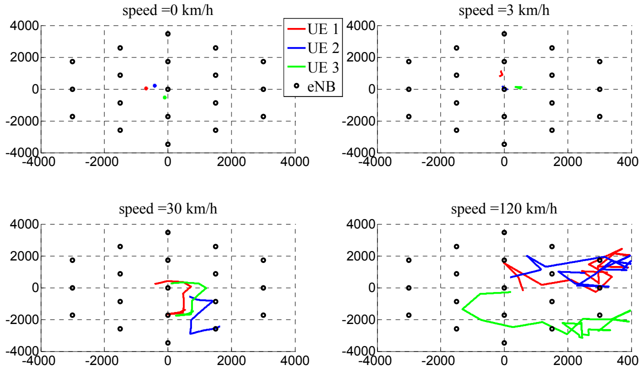


Fig. 5. Traveling pattern of UEs with the Random Walk mobility model.

The user mobility is managed by the *NetworkManager* that, every TTI updates the user position according to the selected mobility model and parameters, and verifies, through the *NetworkManager::HandOverProcedure()* function, if the handover procedure is necessary. In *LTE-Sim* both cell re-selection and hard handover procedures are implemented. Moreover, handover decisions are carried out by the *HandOverManager*, defined for each UE. Hard handover management consists of the following steps:

1) for the UE that triggered the handover procedure, the function *HandOverManager::SelectTargetENodeB()* is used for selecting a new target eNB. Among all eNBs, the one closest to the moving UE is chosen. However, more sophisticated policies can be defined for selecting a new eNB by extending the *NetworkManager HandOverManager* and classes.
2) All the information about the UE are transferred from the old eNB to the new one.
3) Between the UE and the new target eNB, a new radio bearer is created.
4) The UE updates the list of available sub-channels for downlink and uplink, according to those assigned to the new target eNB.

During the handover, the UE switches to a detached state for a given time interval, so that no flows directed to and coming from the UE can be scheduled; such a time interval is a simulator parameter and can be modified (default value is 30 ms).

IV. Flow Management and LTE protocol stacks

In LTE specifications, the EPS bearer has been introduced to provide QoS differentiation. It maps a flow into a logical channel established between the UE and the GW. Moreover, a radio bearer is associated to each EPS bearer as a logical channel between UE and eNB [18].

Both EPS and radio bearers can be classified as default or dedicated. The former is created when the UE is associated to the network and remains established during the whole lifetime of the connection, providing basic connectivity and exchange of control messages. The latter, instead, is established to support a new specific service, e.g., call, video call, web browsing. Orthogonally, bearers can be also classified as guaranteed bit rate (GBR) or non-guaranteed bit rate (non-GBR), according to the QoS requirements of the flow they map. In particular, the default bearer is a non-GBR; a dedicated bearer can be GBR or non-GBR [19]. In the current version of the software, only dedicated radio bearers have been developed.

A. QoS and Radio Bearer

The *Bearer* class models the dedicated radio bearer. When a downlink (uplink) flow starts, it activates a dedicated radio bearer between eNB and UE (UE and eNB) and vice versa. Moreover, for each UE and eNB, it is possible to activate more than one bearer.

QoSParameters object provides, for each *Bearer*, the definition of flow QoS requirements [20], such as the QoS Class Identifier, the allocation and retention priority (composed by the pre-emption flow capability and the pre-emption flow vulnerability), the Guaranteed Bit Rate, and the Maximum Bit Rate.

An IP-based packet classifier is used to map packets coming from the IP layer to a given radio bearer, according to the parameters stored in the *ClassifierParameters* class. The packet classification is done using a packet filter based on the classical five-tuple: source and destination IPs, sender and receiver ports, and protocol type. This functionality has been implemented in the *Classifier* class, defined for all the network elements.

B. The Application Layer

Packets transported by a dedicated radio bearer are generated at the application layer by four different traffic generators: trace-based, VoIP, CBR, and infinite-buffer. The *trace-based* application sends packets based on realistic video trace files, which are available on [21].

The *VoIP* application generates G.729 voice flows. In particular, the voice flow has been modeled with an ON/OFF Markov chain, where the ON period is exponentially distributed with mean value 3 s, and the OFF period has a truncated exponential pdf with an upper limit of 6.9 s and an average value of 3 s [22]. During the ON period, the source sends 20 bytes sized packets every 20 ms (i.e., the source data rate is 8 kbps), while during the OFF period the rate is zero because the presence of a Voice Activity Detector is assumed. It is important to note that these parameters can be modified defining their values into the constructor of the *VoIP* class or using the methods we provided to set them.

The *CBR* application generates packets with a constant bit rate. In particular, packet size and inter-arrival packet time can be defined for this kind of traffic.

Finally, the *Infinite-Buffer* application models an ideal greedy source that always has packets to send.

For each of these applications, a dedicated class has been developed, namely *InfiniteBuffer*, *VoIP*, *CBR*, and *TraceBased*. It is important to note that these classes are extended from the *Application* class that provides methods and parameters common to all of them, such as starting/stopping time instants.

Each application uses the $Application :: Send()$ method to generate a packet. Then, the application delivers it to the network device, calling the function $NetworkNode :: EnqueuePacket()$. When a network device receives a packet from the application, it forwards the packet through the user plane protocol stack (see next Section for details) in order to add protocol headers. Then, the packet is enqueued at MAC layer and associated to a particular bearer, using the *Classifier* functionalities. Now, the packet can be sent on the channel and received from another network device, according to the scheduling decisions. When a network device receives packets from the channel, it forwards them to the upper layer through the same user plane protocol stack; then, it delivers them to the proper application sink.

C. The Protocol Stack

LTE-Sim implements several functionalities of both user-plane and control-plane LTE protocol stacks [23]. To this aim, the *ProtocolStack* class has been created as a container of RRC, PDCP, and MAC entities. An instance of this class, namely *m_protocolStack*, has been defined for each device. Furthermore, as proposed in [24], a RLC entity has been created for each dedicated radio bearer.

The RRC Entity manages downlink and uplink dedicated radio bearers for a given device. It interacts with the classifier in order to classify a packet into a proper radio bearer.

The PDCP Entity provides the header compression of packets coming from the upper layer that will be enqueued into a proper MAC queue.

The RLC Entity models the unacknowledged data transmission at the RLC layer. We have chosen to implement the unacknowledged mode for the RLC because it represents the most used data transmission mode, especially by delay-sensitive and error-tolerant application (such as VoIP and Video streaming). The most important functionalities we have defined for the RLC layer are the segmentation and the concatenation of service data units.

The MAC Entity provides, for both UE and eNB devices, an interface between the device and the PHY layer designed to delivery packets coming from the upper layer to the PHY one and vice versa. Moreover, into this class the AMC module is also defined. *EnbMACEntity* class adds further functionalities, such as uplink and downlink packet schedulers, to the eNB. An example of the interaction among the entities included in the implemented protocol stack is illustrated in Fig. 6: it shows the packet path starting from the application layer and following the user plane protocol stack.

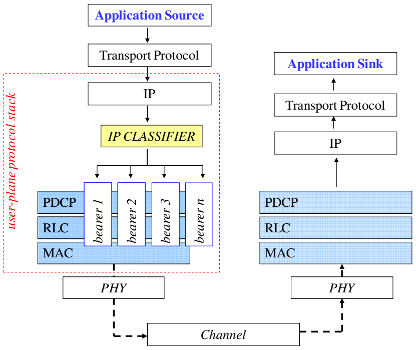


Fig. 6. Implemented protocol stack.

The LTE packet is modeled by the *Packet* class. Three important variables are defined for the packet object: $m\_timeStamp$, m_size, and $m\_packetHeaders$. The $m\_timeStamp$ variable represents the instant the packet is generated at the application layer. This value is used to compute one-way packet delay (it could also be used for statistical purpose and by scheduling strategies). The m_size and $m\_packetHeaders$ variables represent the packet size and the list of protocol headers that have been added to the packet, respectively. When the packet is created, m_size is equal to the amount of data generated by the application layer. As soon as a new header protocol is added to the packet, m_size is updated according to its size.

In the current release of *LTE-Sim*, only the UDP protocol has been developed at the transport layer. However, it is possible to implement other transport protocol (i.e., TCP), extending the *TransportLayer* class.

During the simulation, the application layer creates packets which are passed to the UDP and the IP protocols. As we have explained in Sec. IV-A, an IP-based packet classifier is used to map IP datagrams to radio bearers.

Each bearer maintains its own FIFO (First In First Out) transmission queue, using the *MACQueue* class. When an IP packet is enqueued, a PDCP header is added. Since the PDCP protocol provides an header compression functionality using the robust header compression (ROHC) protocol [25], the packet size is updated in order to compress RTP/UDP/IP headers to 3 bytes [26].

Finally, when the packet is dequeued, CRC trailer and RLC and MAC headers are added.

V. Channel structure and Resource Management

The LTE radio access is based on Orthogonal Frequency Division Multiplexing (OFDM) and provides a highly flexible bandwidth (from 1.4 to 20 Mhz). Both frequency division duplex (FDD) and time-division duplex (TDD) multiple access techniques are supported [14].

Radio resources are distributed among users in a time-frequency domain. The eNB schedules radio resources among uplink/downlink flows at the beginning of each sub-frame.

LTE-Sim supports all six channel bandwidths (i.e., 1.4, 3, 5, 10, 15, and 20 MHz) available for the LTE system [27] and the cellular frequency reuse. Finally, TDD and FDD are handled by the *FrameManager*.

A. Bandwidth Manager

All devices should know the operative bandwidth and available sub-channels for both uplink and downlink. Thus, a dedicated class, i.e., the *BandwidthManager*, has been developed to store these informations. An instance of the *BandwidthManager* class is defined for each PHY object and instances of devices belonging to the same cell store the same information.

B. Frequency reuse

A fundamental implemented feature is the frequency reuse concept [28]. As well known, the frequency reuse increases both coverage and capacity of the cellular network and reduces the inter-cell interference. The idea is that each cell does not use all the available sub-channels but only a subset, in a way that adjacent cells utilize different subsets of sub-channels. A group of cells, using together the complete set of available sub-channel, forms a *cluster* that is regularly replicated in order to cover the whole service area.

The *NetworkManager::RunFrequencyReuse()* function has been developed to apply frequency reuse techniques and distribute the available bandwidth among cells. As described in [29], the number of cells that form the cluster depends from the E-UTRAN operative band and from the downlink (uplink) bandwidth.

At the present, *LTE-Sim* supports all possible cluster configurations available for the first E-UTRAN operative band (i.e., [1929-1980] MHz for the UL and [2110-2170] MHz for the DL, in FDD mode) [27].

The *NetworkManager::RunFrequencyReuse()* function receives the following parameters as input: (i) the number of cells, (ii) the cluster size, and (iii) the downlink (uplink) bandwidth. It distributes the whole available bandwidth among clusters in order that all cells belonging to the same cluster have not overlapping channels. After applying the frequency reuse technique, it returns a list of *BandwidthManager* objects that should be be assigned to devices belonging to each cell. Fig. 7 shows examples of the result of the implemented frequency reuse technique.

It is important to note that even if currently the list of sub-channels assigned to a cell remains constant during the simulation, it is possible to implement more sophisticated frequency reuse algorithms, extending the *NetworkManager* class.

When the handover procedure occurs, the UE updates the list of available sub-channels for downlink and uplink, according to those assigned to the new target eNB.

C. Frame Structure

LTE-Sim supports two frame structure types proposed in [14] for the E-UTRAN. The first one is defined for FDD mode and it is called *frame structure type 1*. The second one is called *frame structure type 2* and is defined for TDD mode. For the frame structure type 1, the bandwidth is divided into two parts, allowing downlink and uplink data transmissions, simultaneously in the time. For the frame structure type 2, the LTE Frame is divided into two consecutive half-frames, each one lasting 5 ms (see Fig. 8).

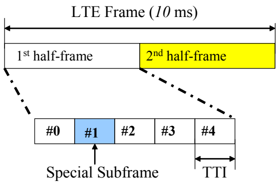


Fig. 8. Frame type 2 for TDD mode

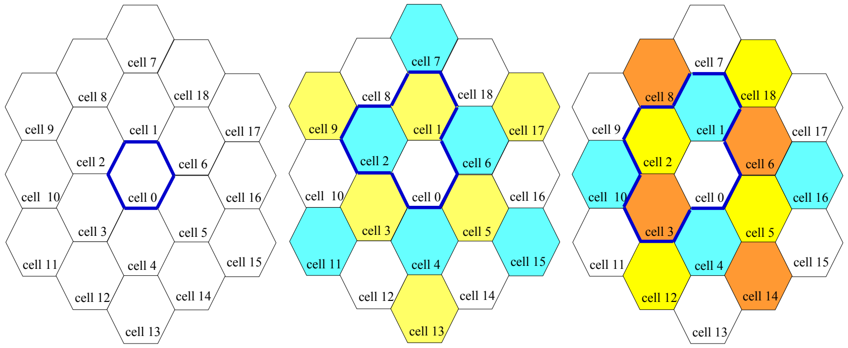
Moreover, a special sub-frame in each half-frame is reserved for other purposes and is not used for data transmission. In a real LTE network, this sub-frame is used to send downlink and uplink pilot symbols, separated by a Guard Period.

According to [14], Tab. II reports seven implemented uplink-downlink configurations of type 2 (TDD) frame. We note that sub-frames 0 and 5 are always reserved for downlink transmission.

The frame structure and the TDD frame configuration have been defined in the *FrameManager*. During the simulation, the *FrameManager* schedules LTE frame and sub-frames and decides, according to the frame structure, if a sub-frame will be used for the uplink, for the downlink, or for both of them.

D. Radio Resource Scheduling

The most important objective of LTE scheduling is to satisfy Quality of Service (QoS) requirements of all users by trying



(a) (b) (c)

Fig. 7. Implemented frequency reuse techniques with cluster of (a) 1, (b) 3, and (c) 4 cells.

TABLE II
FRAME TYPE 2 CONFIGURATIONS

configuration	sub-frame number									
	1^{st} half frame					2^{nd} half frame				
number	0	1	2	3	4	5	6	7	8	9
0	D	S	U	U	U	D	S	U	U	U
1	D	S	U	U	D	D	S	U	U	D
2	D	S	U	D	D	D	S	U	D	D
3	D	S	U	U	U	D	D	D	D	D
4	D	S	U	U	D	D	D	D	D	D
5	D	S	U	D	D	D	D	D	D	D
6	D	S	U	U	U	D	S	U	U	D

D = downlink sub-frame; U = uplink sub-frame; S = Special Sub-frame.

to reach, at the same time, an optimal trade-off between utilization and fairness [23]. This goal is very challenging, especially in the presence of real time multimedia applications, which are characterized by strict constraints on packet delay and jitter.

In the LTE system, the concept of channel-sensitive scheduling has been introduced. It exploits the independent nature of fast fading across users. When there are many users that measure a different channel quality, it is highly likely to find a user with good, or relatively good, channel condition at a given time. Based on this idea, Maximum Throughput (MT) and Proportional Fair (PF) have become the most important well-known scheduling strategies for LTE networks [23].

Scheduling decisions are strictly related to the channel quality experienced by each UE, which periodically measures such a quality using reference symbols. Then, CQI feedback are sent to the eNB, using the uplink control messages [23]. This information is used by the scheduler to properly distribute RBs among users. Moreover, CQI feedbacks are also exploited by the link adaptation module to select, for each UE, the most suitable modulation scheme and coding rate at the physical level, trying to maximize the spectral efficiency. This approach is known as Adaptive Modulation and Coding (AMC) and it has been adopted by several wireless technologies, such as EDGE [30] and WiMAX [31]. Further details on AMC will be provided below.

To provide an important support to research activities on scheduling, we have implemented virtual uplink and downlink scheduler classes (called *ULScheduler* and *DLScheduler*, respectively) that offer a basic implementation of some methods common to all scheduling strategies. Moreover, to demonstrate the flexibility of the *LTE-Sim*, we have implemented PF, Modified Largest Weighted Delay First (M-LWDF), and Exponential Proportional Fair (EXP) downlink schedulers [11] in *PF-DLScheduler*, *M-LWDF-DLScheduler*, and *EXP-DLScheduler* classes, respectively.

It is important to remark that it is very simple to add a generic scheduling algorithm, by: (i) creating a new scheduling class or extending an existing one; (ii) inheriting methods from the virtual class; (iii) defining methods for the implementation of scheduling functions.

Both downlink and uplink scheduler objects are defined in the *ENodeB* class. Each scheduler runs the uplink/downlink scheduling algorithm using the $DoSchedule()$ method, defined into the proper scheduler class. In details, at the beginning of each sub-frame, the *FrameManager* handles the uplink/downlink resource allocation algorithm for all eNBs.

In the next subsection we will overview the implementation of all downlink schedulers provided within the current release of *LTE-Sim*.

E. Downlink Schedulers

At the beginning of each sub-frame, the scheduler selects all flows that can be scheduled. We remark that a flow can be scheduled if and only if it has data packets to transmit at the MAC layer and the receiver UE is not in the idle state.

Every TTI, the scheduler computes a given *metric* for each flow which can be scheduled. We will refer to $w_{i,j}$ as the *metric* assigned to the i-th flows for the j-th sub-channel. Scheduling algorithms differ in the way the *metric* is calculated.

Scheduler works by assigning each j-th sub-channel to the flow with the highest $w_{i,j}$. Thus, the scheduling procedure can be summarized as follows:

1) The eNB creates a list of downlink flows having packets to transmit (i.e., $FlowsToSchedule$); that is, the list of flows which can be scheduled in the current sub-frame.
2) In such a $FlowsToSchedule$ list, MAC queue length and CQI feedbacks are stored for each flow.
3) According to the scheduling strategy, the chosen metric is computed for each flow in the $FlowsToSchedule$

list.

4) The eNB assigns each sub-channel to the flow that presents the highest metric. It is important to remark that the eNB, during the resource allocation procedure, considers the quota of data that each flow has already sent. Therefore, as soon as a flow sends all enqueued packets, its record is deleted from the $FlowsToSchedule$ list.
5) For each scheduled flow, the eNB computes the size of transport block, i.e., the quota of data that will be transmitted at the MAC layer during the current TTI. In detail, the eNB uses the AMC module (defined into the *Phy* object) to map the CQI feedback with the proper modulation and coding scheme (MCS). Then, it can obtain the Transport Block (TB) size from the selected MCS, that is the quota of binary data at the physical layer.

At the end of the scheduling procedure, the eNB calls the *Bearer::Dequeue()* function of all scheduled flows that provides the dequeue of packets at the MAC layer.

To obtain the metric, scheduler algorithms usually need to know the average transmission data rate, $\overline{R_i}$, of the i-th flow, and the instantaneous available data rate of the receiver UE for the j-th sub-channel. This knowledge is useful when the metric has to take into account information about the performance guaranteed in the past to each flow in order to perform fairness balancing. In particular, every TTI, the estimation of $\overline{R_i}$ is given by

$$\overline{R_i}(k) = 0.8\overline{R_i}(k-1) + 0.2R_i(k) \tag{1}$$

where $R_i(k)$ is the data rate achieved by the i-th flow during the k-th TTI and $\overline{R_i}(k-1)$ is the estimation in the previous TTI.

In what follows, we will describe how each implemented downlink scheduler computes the metric.

1) The PF Scheduler: It assigns radio resources taking into account both the experienced channel quality and the past user throughput [32]. The goal is to maximize the total network throughput and to guarantee fairness among flows. For this scheduler, the metric $w_{i,j}$ is defined as the ratio between the instantaneous available data rate (i.e., $r_{i,j}$) and the average past data rate. That is, with reference to the i-th flow in the j-th sub-channel:

$$w_{i,j} = \frac{r_{i,j}}{\overline{R_i}} \tag{2}$$

where $r_{i,j}$ is computed by the AMC module considering the CQI feedback that the UE hosting the i-th flow have sent for the j-th sub-channel; and $\overline{R_i}$ is the estimated average data rate.

2) The M-LWDF Scheduler: It supports multiple data users with different QoS requirements [11]. For each real-time flow, considering a packet delay threshold τ_i, the probability δ_i is defined as the maximum probability that the delay, $D_{HOL,i}$, of the head of line packet (i.e., the first packet to be transmitted in the queue) exceeds the delay threshold.

To prioritize real time flows with the highest delay for their head of line packets and the best channel condition, the metric is defined as:

$$w_{i,j} = \alpha_i D_{HOL,i} \cdot \frac{r_{i,j}}{\overline{R_i}}. \tag{3}$$

where $r_{i,j}$ and $\overline{R_i}$ have the same meaning of symbols in eq. (2) and α_i is given by

$$\alpha_i = -\frac{\log \delta_i}{\tau_i}. \tag{4}$$

Instead, for non real time flows, the considered metric is the one of the simple PF.

Note that, in the current implementation of the M-LWDF allocation scheme, packets belonging to a real-time flow are erased from the MAC queue if they are not transmitted before the expiration of their dead-line. This operation is required to avoid bandwidth wasting. This implementation is not available for the PF, because it is not designed for real-time services.

3) The EXP Scheduler: It has been designed to increase the priority of real time flows with respect to non real time ones, where their head of line packet delay is very close to the delay threshold [11]. For real time flows, the considered $metric$ is computed by using the following equations:

$$w_{i,j} = \exp\left(\frac{\alpha_i D_{HOL,i} - \chi}{1+\sqrt{\chi}}\right)\frac{r_{i,j}}{\overline{R_i}} \tag{5}$$

where symbols have the same meaning of the ones in eqs. (2) and (3) and

$$\chi = \frac{1}{N_{rt}}\sum_{i=1}^{N_{rt}} \alpha_i D_{HOL,i} \tag{6}$$

with N_{rt} being the number of active downlink real time flows.

Instead, for non real time flows, the considered metric is the one of the simple PF. Also with EXP algorithm, packets belonging to a real-time flow are erased from the MAC queue if they are not transmitted before the expiration of their deadline.

F. Channel and Physical Layer

The simulation of a complete PHY layer is not suited for complex network scenarios (including the entire protocol stack), as it requires an high computational effort [33]. For example, the simulator proposed in [9], that implements a complete LTE PHY layer, requires more than 3 hours to simulate few seconds of a network composed by only 2 nodes. This effort can be greatly reduced by employing system-level simulators in which the physical layer is described by an analytic model.

For this reason, we chose an analytical model approach in *LTE-Sim*, which has been successfully used also in other wireless network simulators already developed for analogous technologies and freely available for the community (such as WiMAX in ns-3 [34], Numbat module in Omnet++ [35], and UMTS model in ns-2 [36]).

Channel and *Phy* classes model channel and LTE physical layer, respectively. For all network devices, an instance of the *Phy* class, named *m_phy*, has been defined and it is attached to a given channel in order to accomplish several functionalities: (i) the estimation of SINR (Signal to Interference and Noise Ratio); (ii) the selection of a proper MCS before packets transmission (in particular, such a function is provided by the AMC module); (iii) the access to the channel, in order to allow transmission and reception of packets.

1) Channel: It has been developed to handle packet transmission, taking into account the propagation loss model. To manage separately downlink and uplink, a couple of channels must be defined for each cell. Moreover, each PHY object stores into variables $m\_downlinkChannel$ and $m\_uplinkChannel$ a pointer to channels created for a cell the device belongs to.

The *Channel* class has a private structure named $m\_devices$ which handles all the physical objects connected to it.

When a PHY instance has to send packets on a set of sub-channels, it calls the *Channel::StartTx* method of a proper channel object (i.e., the downlink channel for the eNB and the uplink channel for the UE), passing a list of packet to send and the transmission power. *Channel::StartTx* handles packet transmission in two consecutive steps. It first calculates, for each attached physical device, the propagation losses according to the propagation loss model (see below for details) and updates the power of the transmitted signal. Then, it forwards packets to all physical devices attached to it and calls the reception procedure (see below for details on such a procedure).

2) Propagation Loss Model: Class *PropagationLossModel* models the channel propagation of the E-UTRAN interface. This class has been developed to compute the transmitted signal propagation losses.

To support various cell scenarios (i.e., urban micro-cell, suburban macro-cell, urban macro-cell and rural macro-cell), a virtual class *ChannelRealization* has been developed to provide a basic implementation of both propagation and channel models; it realizes the channel condition in terms of loss and interference. As proposed in [15], a realization of the channel condition should consider four different phenomena: (i) the path loss, (ii) the penetration loss, (iii) the shadowing, and (iv) the effect of fast fading due to the signal multipath.

The variable $m\_channelRealizations$, defined into the *PropagationLossModel* class, stores a *ChannelRealization* object for each couple of devices attached to a given channel. During packet transmissions, knowing the source device and the destination device, a *ChannelRealization* object is selected and associated to them forming the $m\_channelRealizations$ variable. Then, the *ChannelRealization::ComputePropagationLoss()* is called to compute the loss due the propagation.

To understand how the propagation loss model works, we can analyze what happens in a downlink transmission.

Let $P_{TX,j}$ and $P_{RX,i,j}$ be the eNB transmission power and the reception power of the i-th UE for the j-th sub-channel, respectively. $P_{RX,i,j}$ is given by:

$$P_{RX,i,j}|_{dB} = (P_{TX,j} - M_{i,j} - L_i - T_i - S_{i,j})|_{dB} \tag{7}$$

where $M_{i,j}$, L_i, T_i, and $S_{i,j}$ are the losses due to multipath, path loss, penetration, and shadowing. Note that all these variables are expressed in dB.

To simulate cell scenarios with different propagation loss model, we have implemented three possible channel realizations: (i) a macro-cell channel realization for urban and suburban areas, (ii) a macro-cell channel realization for the rural area, and (iii) a micro-cell channel realization. For each of these models, a dedicated class, which inherits from the *ChannelRealization* class, has been developed.

As default, the large scale shadowing fading has been modeled trough a log-normal distribution with 0 mean and 8 dB of standard deviation. The penetration loss, instead, is set to default value of 10 dB [15]. It is possible to modify these values according to the simulated cell environment.

Tab. III reports path loss models used for each of the implemented cell scenarios [37][38]. Note that d is the distance between the eNB and the UE in kilometers.

At the present, the fast fading has been modeled for all the implemented propagation models with the Jakes model [39] for the Rayleigh fading, taking into account the user speed, the sub-carrier frequency (i.e., the central frequency of the j-th sub-channel), and a number of multiple paths uniformly chosen in the set [6, 8, 10, 12] [40]. Fig. 9 shows an example of multipath realizations when users speeds are equal to 0, 3, 30, and 120 km/h.

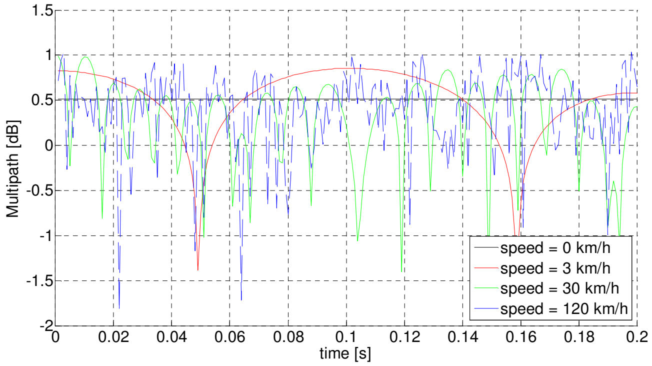


Fig. 9. Fast Fading realization.

It is worth to note that a new channel model can be easily added to the *LTE-Sim*, extending the *ChannelRealization* class.

3) UE Reception Procedure: When the i-th UE receives packets, it executes the follows steps:

- the physical layer computes for each sub channel the SINR for the received signal considering the received power, the noise, and the interference, as it follows:

$$SINRi,j = \frac{P_{RX,i,j}}{(FN_0B) + I}. \tag{8}$$

  where F, N_0, B_j, and I are the noise figure (default value 2.5), the noise spectral density (default value -174 dBm), the bandwidth of a resource block (i.e., 180 kHz), and the interference, respectively.

  We remark that the interference is the total power received from the eNBs sharing the same frequency resources. The propagation loss of the interfering power are calculated by the *NetworkManager* through the *ComputePathLossForInterference ()* method, that selects the proper propagation loss model depending on the cell scenario.
- According to the CQI reporting mode, the UE creates CQI feedbacks to send to the eNB.
- The physical layer determines if packets have been received correctly. To this aim, for each sub-channel, used

TABLE III
IMPLEMENTED PATH LOSS MODELS

Cell scenario	Path loss model
Macro Cell - Urban and Suburban Areas	$L = 128.1 + 37.6 \log_{10} d$ @ 2GHz.
Macro Cell - Rural Area	$L = 100.54 + 34.1 \log_{10} d$ @ 2GHz.
Micro Cell	$L = 24 + 45 \log_{10}(d + 20)$.

to transmit that packet, the Block Error Rate (BLER) is estimated, that is the ratio between the number of erroneous received blocks (i.e., the transport block with wrong CRC) and the total number of sent blocks [41].

The BLER is obtained considering both MCS used for the transmission and SINR that the device has estimated for the considered sub-channel. In particular, the BLER value is drawn using stored BLER-SINR curves obtained through a LTE link level simulator [9]. In *LTE-Sim* different sets of BLER-SINR curves are stored and the choice of the proper set depends on several physical parameters. As an example, the curves for 1.4 MHz bandwidth and a SISO (Single Input Single Output) transmission scheme over an AWGN channel are shown in Fig. 10. According to the proper BLER-SINR curve (depending on the used MCS), the simulator estimates if the packet has been correctly received or not. In the latter case, the packet is considered erroneous and discarded.

- If the packet has been correctly received, it is forwarded to the upper layers.

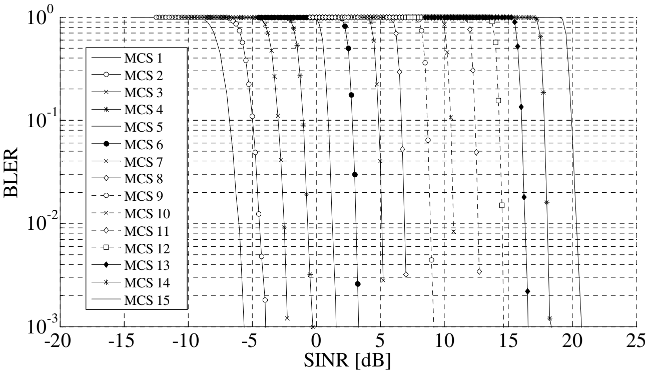


Fig. 10. BLER-SINR curves for 1.4 MHz.

4) Channel Quality Indicator: During the resource allocation process, the eNB can select the most suitable MCS for each scheduled flow with trying to minimize the packet loss due to the channel error.

The UE uses the *CQIManager* to create CQI feedbacks. When the UE receives packets in the downlink, it estimates the SINR for each downlink sub channel. Then, according to the CQI reporting rules, it creates CQI feedbacks to send to the eNB where it is registered.

The CQI is used by the UE to report to the eNB the highest data rate that can be achieved over a given sub-channel while guaranteeing a BLER at least equal to a certain BLER target (the default value is 10%). In particular, the CQI value is obtained as a quantized version of the estimated SINR. The mapping procedure between SINR and CQI is performed again through the BLER-SINR curves (Fig. 10). Using these mapping tables, it is possible to select the best MCS (in terms of data rate) that for the given SINR guarantees a BLER value smaller than the target BLER. Finally, the reported CQI corresponds to the index of the selected MCS.

As said before, *LTE-Sim* supports both periodical and aperiodical CQI reporting with both full band and wide band reporting modes have been developed. When the periodical CQI reporting is selected, the variable $m\_reportingInterval$, defined into the *CQIManager* class, identifies the time interval every time CQI feedbacks should be created and sent to the eNB. When the aperiodical CQI reporting is selected, instead, the UE creates and sends CQI feedbacks only when it receives a request from the eNB.

5) Adaptive Modulation and Coding Module: The AMC module, implemented into the *AMC* class, has been developed to allow eNB to select, during the resource allocation procedure, the proper modulation and coding scheme for the flow that has to be scheduled. To maximize the spectral efficiency, the MCS is chosen considering the latest CQI value sent by the UE and using the $AMC :: GetMCSFromCQI()$ method. It is important to note that the selection of the MCS allows us to obtain the efficiency (expressed as the number of informative bits per symbols) as described in [16].

6) Determination of Transport Block Size: In LTE systems, the TB is the quota of binary data at the physical layer, coming from the MAC layer during transmission (or passed to the MAC layer during reception) on transport channels [16]. In other words, TB is the number of bytes that a flow can transmit in one or more sub-channels at the MAC layer (including MAC overhead and CRC trailer), during one TTI. The TB size depends on the MCS chosen by the AMC module, the number of antenna ports, the duration of the prefix code used at physical layer, and the number of symbols used by the control channel. The *AMCModule* object uses the table m_TBSize_Table to evaluate the TB size from the selected MCS value. To this aim, it takes into account the configuration proposed in [42]: normal prefix code, 2 antenna ports, 3 OFDM symbols for PDCCH (Physical Downlink Control Channel), no sync signals, and the absence of PBCH Physical Broadcast Channel.

VI. SIMULATION AND PERFORMANCE EVALUATION

In this section, we describe how a LTE scenario can be defined and how to manage the output results. Then, a performance evaluation of the *LTE-Sim* is reported, considering both the software scalability test and the performance evaluation of a realistic LTE networks.

A. Building a LTE topology

With *LTE-Sim*, a LTE scenario can be created as a static function in a C++ header file, that should be stored into the Simulation/Scenarios folder. A reference of this function should be added into the main program. In this way, the user is able to simulate a proper LTE scenario, selecting it directly from the main program.

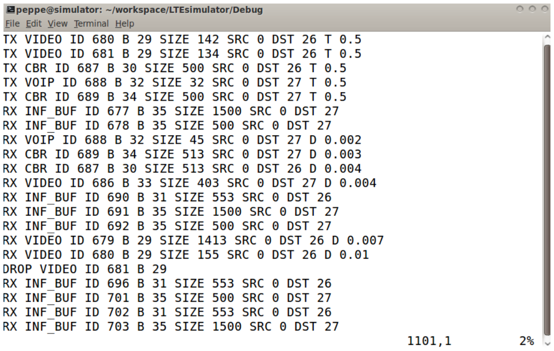
A basic scenario can be created using the following guidelines:

- create an instance for *Simulator*, *NetworkManager*, *FlowsManager*, and *FrameManager* components.
- Create *Cell*, *ENodeB*, and *UE* objects using methods of the *NetworkManager* class. For each of these objects, several parameters can be assigned directly with the constructor of the class.
- Create applications, defining for each of them source and destination, QoS parameters, IP classifier parameters, the start time, and the stop time.
- Define the duration of the simulation and, finally, call the *Simulator::Run()* function.

To simplify the use of the simulator, both single-cell and multi-cell LTE topologies are proposed as examples (both stored into the Simulation/Scenarios folder), where the number of UEs and the number of flows can be specified by command line.

B. Tracing results

The current version of the simulator provides a sophisticated tracing functionality. The trace is displayed directly during the execution of the simulation. An example of the output trace is reported in Fig. 11.


peppe@simulator: ~/workspace/LTEsimulator/Debug
File Edit View Terminal Help

```
TX VIDEO ID 680 B 29 SIZE 142 SRC 0 DST 26 T 0.5
TX VIDEO ID 681 B 29 SIZE 134 SRC 0 DST 26 T 0.5
TX CBR ID 687 B 30 SIZE 500 SRC 0 DST 26 T 0.5
TX VOIP ID 688 B 32 SIZE 32 SRC 0 DST 27 T 0.5
TX CBR ID 689 B 34 SIZE 500 SRC 0 DST 27 T 0.5
RX INF_BUF ID 677 B 35 SIZE 1500 SRC 0 DST 27
RX INF_BUF ID 678 B 35 SIZE 500 SRC 0 DST 27
RX VOIP ID 688 B 32 SIZE 45 SRC 0 DST 27 D 0.002
RX CBR ID 689 B 34 SIZE 513 SRC 0 DST 27 D 0.003
RX CBR ID 687 B 30 SIZE 513 SRC 0 DST 26 D 0.004
RX VIDEO ID 686 B 33 SIZE 403 SRC 0 DST 27 D 0.004
RX INF_BUF ID 690 B 31 SIZE 553 SRC 0 DST 26
RX INF_BUF ID 691 B 35 SIZE 1500 SRC 0 DST 27
RX INF_BUF ID 692 B 35 SIZE 500 SRC 0 DST 27
RX VIDEO ID 679 B 29 SIZE 1413 SRC 0 DST 26 D 0.007
RX VIDEO ID 680 B 29 SIZE 155 SRC 0 DST 26 D 0.01
DROP VIDEO ID 681 B 29
RX INF_BUF ID 696 B 31 SIZE 553 SRC 0 DST 26
RX INF_BUF ID 701 B 35 SIZE 500 SRC 0 DST 27
RX INF_BUF ID 702 B 31 SIZE 553 SRC 0 DST 26
RX INF_BUF ID 703 B 35 SIZE 1500 SRC 0 DST 27
                                                  1101,1         2%
```

Fig. 11. Example of Output trace.

With reference to the figure, the first field describes the event which has triggered the tracing. In particular, rows starting with *TX*, *RX*, and *DROP* are associated to packets that have been sent, received, and dropped, respectively. The second field describes the packet type to which the trace refers to. Other fields are described in the follows:

- ID = Identifier. It identifies the packet uniquely.
- B = Bearer ID. It identifies the bearer used to map the packet.
- SRC = Source ID. It identifies the node that sends the packet.
- DST = Destination ID. It identifies the node that receives the packet.
- T = Time. It represents the instant in which the packet is created.
- D = Delay. It represents the delay of the received packet.

C. The scalability test

To present a scalability test of *LTE-Sim*, several simulations have been executed. An LTE network composed by 19 cells with radius equal to 1 km as been considered, varying the number of UEs in the range [190-950]. Such users are uniformly distributed among cells. UEs travel with speed equal to 3 km/h, using the Random Walk mobility model [17].

For each UE, a downlink VoIP flow has been considered. All flows are active during the whole simulation. Each simulation lasts 100 s. Simulation has been done using a Linux machine with a 2.6 GHz CPU and 4 GBytes of RAM.

Figs. 12 and 13 show the memory and the time required to execute the simulation, respectively.

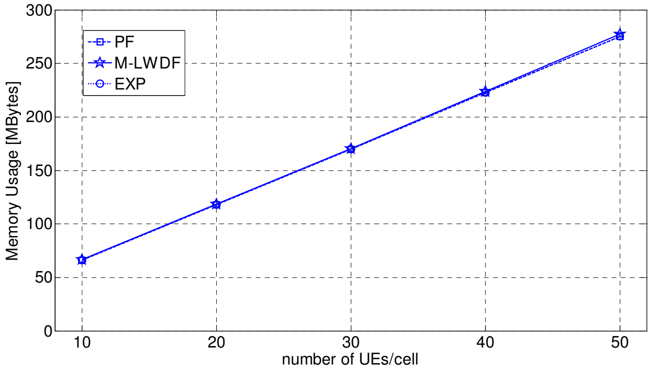


Fig. 12. Memory required vs. number of UEs.

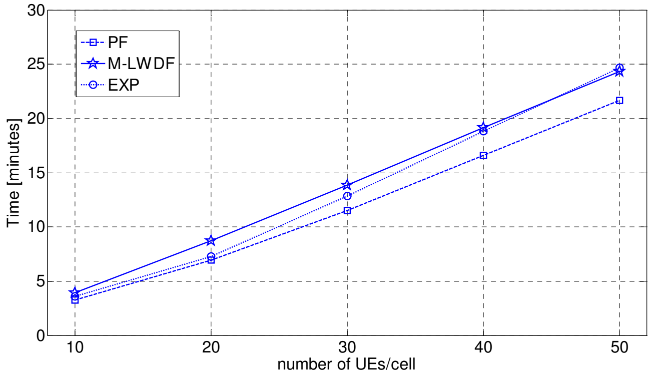


Fig. 13. Simulation time vs. number of UEs.

The memory used to execute the simulation increase with the number of UEs and it is independent on the scheduling algorithm used by the eNB. Moreover, the time required to execute the simulation increases with the number of UEs; it depends on the scheduling algorithm used by the eNB. In fact, the PF algorithm requires less time than other scheduling strategies due to its very simple implementation.

An important results is that *LTE-Sim* requires a limited amount of memory and simulation time, also with high load scenarios.

D. Performance Evaluation

Herein, a performance evaluation of the implemented downlink scheduling algorithms (i.e., PF, M-LWDF, and EXP) is reported. A realistic scenario is considered: there are 19 cells, with the radius equal to 1 km, where a number of UEs (chosen in the range [10 - 30]) are uniformly distributed into each cell. UEs travel inside the area following the Random Walk mobility model in an urban macro cell scenario.

The whole bandwidth is distributed among cluster of 4 cells, to guarantee 10 MHz of bandwidth in the downlink, for each cell.

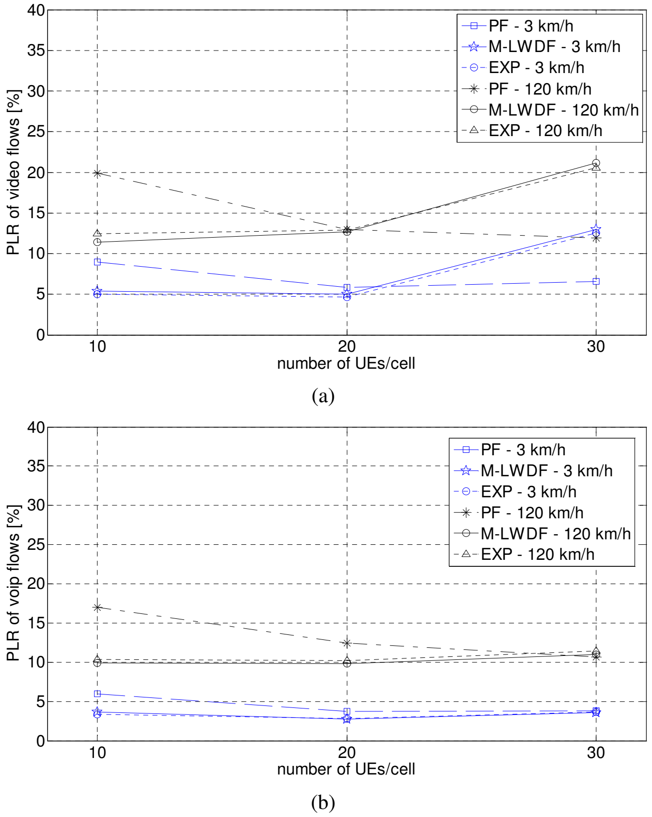
Each user receives one H.264 video flow (encoded at 128 kbps), one VoIP flow, and one best effort flow modeled with the infinite buffer application.

The performance of PF, M-LWDF, and EXP schedulers have been analyzed, varying the user speed in the range [3, 120] km/h.

Fig. 14 shows the packet loss ratio (PLR) experienced by video and VoIP flows. As expected, the PLR increases with the user speed because the link adaptation procedure is impaired at the high velocity. Furthermore, we note a different behavior between the schedulers designed for real-time services (i.e., M-LWDF and EXP) and the PF scheduler. When M-LWDF and EXP schedulers are used, the PLR increases with the number of UEs. The reason is that in scenarios with high number of concurrent real-time flows, the probability to discard packets for dead-line expiration increases. When the PF scheduler is used, instead, the PLR decreases as the number of UEs increases. In this case the reason is that in a scenario with high load factor, the PF scheduler can exploits the multiuser diversity gains, reducing the loss probability at the PHY layer. It is important to note that in this case, the PLR only counts for the PHY losses and that it cannot grants for bounded packet delays. This effect can be easily seen in Fig. 15 where the average packet delays of real-time flows is reported.

The behavior of best effort flows has been also studied; Fig. 16 shows the achieved goodput. Its value has been averaged among all cells. As expected, the goodput decreases as the user speed increases, due to the worse channel quality measured by the receiver UE. Also the Jain Fairness index [43] has been computed, considering the goodput achieved by best effort flows at the end of each simulation. In all operative conditions the index is very close to 0.9, meaning that all considered scheduling strategies provide comparable levels of fairness.

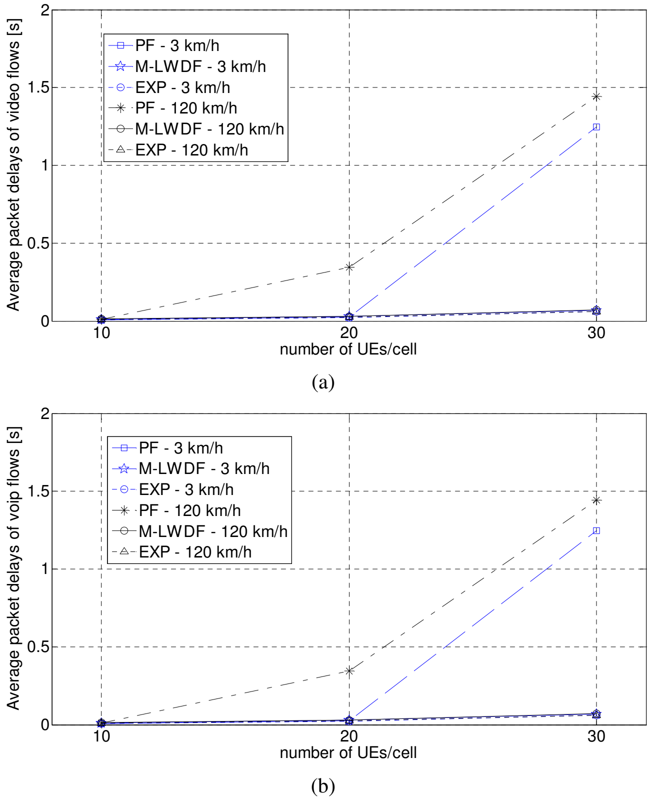
Finally, Fig. 17 shows the cell spectral efficiency achieved for the considered LTE scenarios and expressed as the total throughput achieved by all users divided by the available bandwidth [44]. As expected, different schedulers impact differently. When the number of users in the cell increases, QoS-aware schedulers such as M-LWDF and EXP still try to guarantee QoS constraints to a high number of flows, with a consequent negative impact on the system efficiency. On the other hand, when the number of users increases from 10 to 20,



(a)

(b)

Fig. 14. Packet Loss Ratio of (a) video and (b) voip flows.



(a)

(b)

Fig. 15. Average packet delays of (a) video and (b) voip flows.

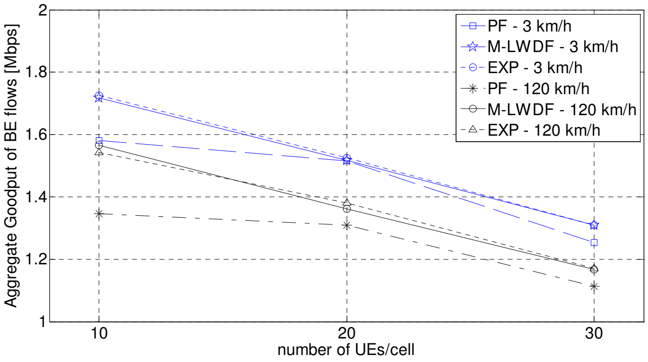


Fig. 16. Goodput achieved by best effort flows.

the PF scheduler is able to exploit the gain of the multiuser diversity while granting a high fairness index (i.e. 0.9). When the number of users further increases, the same fairness index is reached by the PF scheduler at the cost of a limited drop in the cell spectral efficiency.

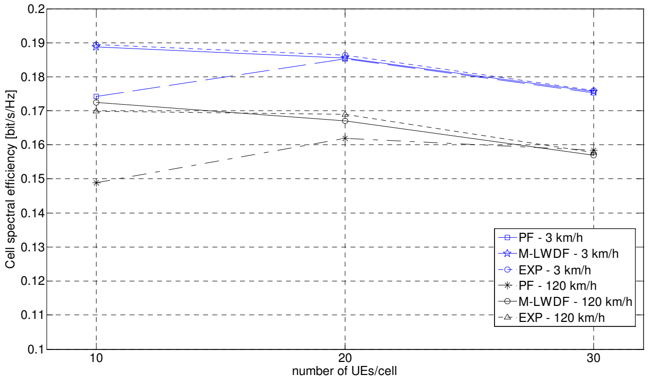


Fig. 17. Cell spcetral efficiency.

VII. Conclusion

In this paper a new open source framework to simulate LTE networks, namely *LTE-Sim*, has been proposed. Features covered by this simulator will allow both researchers and practitioners to test enhanced techniques for improving 4G cellular networks, such as new physical functionalities, innovative network protocols and architectures, high performance scheduling strategies, and so on. The open nature of this software can allow people interested in research in this field to contribute to the development of the framework, furnishing a reference platform for testing and comparing new solution for LTE systems.

Effectiveness of the developed simulator has been verified with several simulations to study the scalability and the performance of the framework. Moreover, *LTE-Sim* has been applied to compare several scheduling strategies and to evaluate their performance. In the near feature, we plan to improve the simulator implementing new features, such as HARQ and more sophisticated channel and PHY models, that have not been included in the current version of the software.

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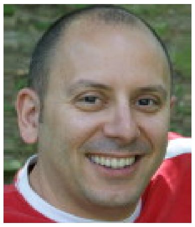

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