iTETRIS Heterogeneous Wireless Communication Platform for the Large-Scale Evaluation of Cooperative Road Traffic Management Policies

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***Abstract*— Cooperative vehicular communications are being developed to improve road safety and traffic management by assisting drivers and road authorities with real-time and comprehensive traffic information. In the study of such systems, large-scale simulation research has been identified as a necessary resource to realistically evaluate cooperative vehicular systems and traffic management policies in city-sized scenarios. In this context, this paper presents the iTETRIS multi-technology wireless simulation platform aimed at providing an optimally, efficiently and well-designed framework for the evaluation of vehicular communications and its potential impact on traffic efficiency. Given the importance of accurately modeling the wireless communication link in simulation researches, this paper also focuses on the modeling and characterization of the 802.11p physical layer by means of link-level simulations.**

Keywords: cooperative vehicular communications, simulation platform, 802.11p physical layer modeling.

I. INTRODUCTION

Wireless vehicular cooperative systems are a promising solution to improve road traffic management through the exchange of traffic information among vehicles and with road infrastructure. Through the use of wireless vehicular communications, cooperative systems will be able to assist the driver allowing the detection of road dangerous situations and road traffic congestions. In addition, the adoption of vehicular communications can be used to ubiquitously provide real-time traffic information and re-route vehicles over optimal paths. In spite of the huge potential benefits that cooperative vehicular systems can bring, there is yet the need to demonstrate the impact of cooperative technologies, in particular with regard to traffic management. The evaluation of road traffic policies requires large-scale studies over long periods of time, which cannot ever be conducted through Field Operational Test (*FOTs*) equipping a limited set of vehicles. To overcome these current limitations, the EU FP iTETRIS (*an Integrated Wireless and Traffic Platform for Real-Time Road Traffic Management Solutions*, http://ict-itetris.eu/) project is developing an integrated simulation platform allowing for large-scale studies on the impact and potential of cooperative vehicular communication technologies to dynamically and efficiently manage road traffic. To achieve its objectives, iTETRIS integrates two widely used open source platforms, SUMO [1] and ns-3 [2]. Whereas SUMO reproduces vehicles' movement taking into account the road topology and traffic rules, ns-3 is employed as the wireless network simulator to model the exchange of messages through V2V (Vehicle-to-Vehicle) and V2I (Vehicle-to-Infrastructure) communications. This paper focuses on the architecture and implementation details of the iTETRIS wireless simulation platform.

From the simulator design perspective, iTETRIS presents several challenges, which mainly arise from the fact that iTETRIS is a multi-technology platform which includes short and long-range communication systems, cellular and ad-hoc technologies as well as an extensive set of communication protocols. Given the demanding scalability requirements of iTETRIS, there exists a challenging trade-off between the level of implementation detail of the communication modules, and the efficiency and simplification of the design required for conducting computationally efficient large-scale simulations. In the implementation and design process of the iTETRIS platform both of these aspects are considered. In this context, and apart from other design approaches aimed at reducing implementation complexity, iTETRIS characterizes the physical layer of the communication protocol stack through PER (*Packet Error Rate*) look-up tables obtained from link-level simulations. Therefore, the physical layer models in the network simulator can be simplified and computational calculation times can be lowered.

II. EUROPEAN ITS COMMUNICATION ARCHITECTURE

The iTETRIS wireless communication architecture is being developed following ETSI standards for Intelligent Transportation Systems (*ITS*). Since ETSI standards are not fully completed yet, input from other projects and initiatives such as COOPERS, CVIS and SAFESPOT, the Car2Car Communication Consortium, IETF, ISO, IEEE and SAE are also being considered in order to make sure that the iTETRIS platform is aligned with the major international and research standardization efforts. The ITS system defined by ETSI [3] and depicted in Figure 1, specifies a new type of communication system dedicated to transportation scenarios, which to a large extent is independent from specific communication technologies and user applications.

As Figure 1 shows, the ITS Communications Architecture covers various communication media and related protocols for the physical and data link layers. The architecture will then include algorithms to select at each point in time the most appropriate communication technology. Different networking modes are identified, such as geo-routing, specific light-overhead ITS protocols, and IPv6 networking with new additions for mobility support. Each networking protocol may be connected to a specific dedicated ITS transport protocol or may connect to already existing transport protocols, e.g. UDP, TCP. The *Facilities* block collects a set of common functionalities which are shared by several applications for various tasks. The facilities provide data structures to store, aggregate and maintain data of different type and source, and make them available to be accessed. The set of facilities are classified into *Application Support*, *Information Support* and *Communication Support* facilities depending on the nature of the functionalities they offer. The *Applications* block presents the ITS user applications making use of the communication services provided by the underlying protocol stack. The *Management* entity is responsible for the configuration of an ITS station and for cross-layer information exchange among the different layers. Some of the main functionalities include the dynamic and optimum mapping of user applications on communication interfaces, the monitoring and managing of the set of communication interfaces, the management of transmission permissions and priorities, and the management of service advertisements depending on application specifications. The *Security* entity provides security services to the communication protocol stack and to the management entity. Further details on the description of the ITS communication architecture can be found in [4].

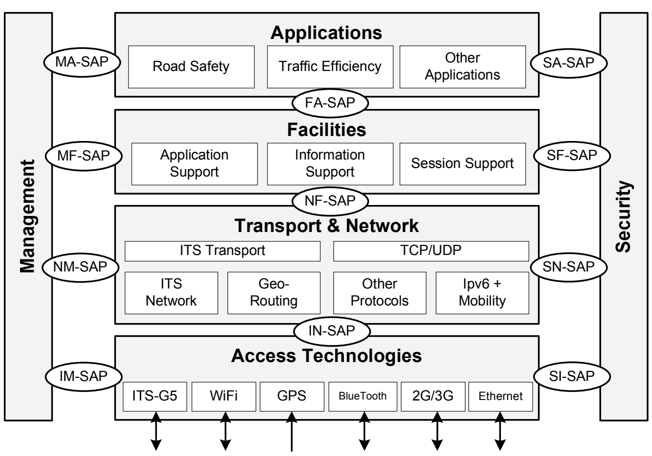

Figure 1. *European ITS Communications Architecture.*

III. iTETRIS WIRELESS COMMUNICATION MODULES

This section presents the group of wireless access technologies considered in iTETRIS and provides the set of functionalities implemented in the platform and how accurate they are modeled looking at the iTETRIS requirements and considering scalability and computational efficiency aspects. It is worth noting that iTETRIS implements a variety of wireless technologies, ranging from short-range and ad-hoc communications (ITS-G5, also referred as 802.11p or WAVE) to broadcast technologies (DVB), as well as cellular systems (UMTS and WiMAX). Whereas ITS-G5 does not require communication infrastructure and is specifically designed to effectively operate in vehicular environments, cellular technologies employ base stations through which communication take place. On the other hand, DVB, as a broadcast technology, allows data transmissions over large areas and to multiple users. This section introduces the currently implemented technologies in iTETRIS: ITS-G5, WiMAX and UMTS.

A. ITS-G5

The iTETRIS wireless simulation platform implements the European profile for ITS in the 5Ghz band, which is also referred as ITS-G5 and is being standardized by ETSI in [5]. ITS-G5 is being developed according to the IEEE 802.11p amendment, the IEEE 1609 standards, and also taking into account the set of ISO standards for vehicular communications, known as CALM (*Communications Access for Land Mobiles*). It is worth noting that since all these standards are still under development, the iTETRIS implementation will be updated accordingly as standards are fully completed and published during the project duration.

1) ITS-G5 operation overview

The ITS-G5 standard is meant to describe the functions and services required by ITS stations to operate in a rapidly varying environment and exchange messages with short connection establishment delays. ITS-G5 is a technology for ad-hoc communications which does not require infrastructure nodes to manage the communication between stations. However, ITS-G5 does not prevent to install infrastructure units to enhance communications. Although ITS-G5 distinguishes different operation modes for various kinds of applications and frequency bands, iTETRIS only considers the ITS-G5A mode which intends to be employed for road safety and traffic management applications. An ITS-G5A station does not need to perform scanning, association and authentication before establishing communication with any other station. All ITS-G5A stations are treated equally as peer stations, irrespective of being vehicles or infrastructure units.

ITS-G5 physical layer

The ITS-G5A mode operates in the 5875-5905 MHz frequency band designated for ITS applications. The 30 MHz bandwidth is divided into 3 sub-channels of 10 MHz, one devoted to operate as control channel (CCH) and the other two as service channels (SCHs). SCH1 is the main service channel for safety and efficiency messages (optimized for high throughput, safety messages with medium priority, multihop and geocast messages at the second hop). SCH2 is a service channel used only with low transmission power for very short range communications, mainly between vehicles and roadside stations. Finally, CCH is the key channel over which vehicles and road side units broadcast their presence and announce available services (optimized for low latency, cyclic network layer packets, high priority safety messages, multihop and geocast messages at the first hop). ITS stations should be always capable of simultaneously receiving on the CCH and on either one of the SCHs, except whilst transmitting in any one of these channels. The ITS-5GA operation mode uses a channel spacing of 10Mhz. This contrasts with the 20Mhz channel spacing usually employed by 802.11a devices. The employment of a 10Mhz channel spacing causes that the data rates are halved with respect to 802.11a, leading to transmission rates of 3, 4.5, 6, 9, 12, 18, 24 and 27 Mbps.

ITS-G5 data link layer

ITS-G5 MAC layer relays on the CSMA medium access. Since collisions may occur with CSMA, especially in congested traffic situations, above a certain network load the system performance may rapidly decrease. Congestion control could be a direct way of preventing this. In this context, ITS-G5 allows upper layers to select, on a packet basis, radio parameters such as transmission power and data rate. Optimally adjusting these parameters, congestion load on the radio channel can be reduced. When it comes to serving application transmission requests, ITS-G5 takes into account the requirements demanded by the applications performing priority and QoS differentiation. ITS-G5 supports packets with different priorities, assigning the highest priority for critical safety information. Concurrent transmissions requests are handled in a way that requests with highest priority are first processed. The EDCA mechanism from IEEE 802.11e is employed.

2) ITS-G5 implementation in iTETRIS

The iTETRIS implementation of ITS-G5 is based on the ns-3 WiFi communication module [6]. In the ns-3 simulation platform, a network device (*NetDevice*) implements a radio interface considering the data link layer and physical layer of the communication protocol stack. The iTETRIS platform includes a set of different NetDevices for modeling each of the technologies considered in the project. In this context, the *ITS-G5NetDevice* fully implements the ITS-G5A communication profile described in the previous section. The iTETRIS ITS-G5 module allows multi-channel operation installing two *ITS-G5NetDevices* in every ITS station. One of the NetDevice always operates on the control channel, whereas the other NetDevice switches among the two service channels (SCH1 and SCH2). It is important to highlight that the current WiFi module is unable to perform channel switching and thus this capability has been implemented in iTETRIS.

According to the ITS-G5 standard and available functionalities in ns-3, the main modifications and enhancements introduced in the iTETRIS platform that have been implemented to allow cooperative vehicular communications are briefly described next:

- *10Mhz channel spacing:* new data rates for 802.11 half-clocked operation have been created. The introduction of new data rates has required modifications in the current PHY and MAC layers.
- *Control of transmission parameters by upper layers/management entity:* ITS-G5 allows upper layers to define transmission parameters on a packet by packet basis. Therefore, congestion control mechanisms can be implemented. This is supported in iTETRIS by defining a set of packet tags, which specify the channel, transmission power and data rate parameters to be used in the communication.
- *Routing of packets to the proper ITS-G5 channel:* since ITS-G5A can operate in three different channels, it has been necessary to implement an *ITS-G5NetDeviceRouter* capable of forwarding packets coming from upper layers to the proper *ITS-G5NetDevice.*
- *Channel switching:* this capability has been modeled by incorporating several modifications in the PHY and MAC layers, and implementing a new entity, namely *ITS-G5SwitchingManager.* The switching manager allows the cancellation, suspension and resumption of pending packet transmissions that were interrupted before the channel switching. In addition, pending packets may be transmitted on a channel which is different from that where packets were initially scheduled to be transmitted on.

B. WiMAX

According to the communications requirements established by the iTETRIS traffic efficiency applications, the WiMAX IEEE 802.16-2004 standard [7] has been selected for implementation in iTETRIS, to the detriment of Mobile WiMAX. The decision has been based on several factors: a) communications are expected to be short and sporadic, and thus soft handovers would not be essential; b) battery management mechanisms are not required; c) Mobile WiMAX features might be shadowed because of the coexistence with other technologies, e.g. UMTS; d) need to reduce the simulation platform complexity and increase the computational efficiency to allow for large-scale investigations.

1) WiMAX operation overview

iTETRIS implements the OFDM multicarrier PHY mode of the IEEE 802.16 standard. Frames of fixed time duration are employed, which are divided into downlink (*DL*) and uplink (*UL*) subframes. The TDD technique is used to separate in time the DL and UL subframes. The 802.16 MAC protocol is connection-oriented, which implies that all communications are expected in terms of connections. There exists a set of connections for management and data traffic exchanges (*management* and *transport connections*), providing different transmission modes to support unicast, broadcast and multicast communications. A node wanting to entry in the network has to run a set of defined procedures, being the first one *Scanning and Synchronization*, in which SSs (*Subscriber Station*s) scan the possible frequency channels and extract operational parameters. After synchronization is achieved, the *UL parameters obtaining* takes places, where SSs discover the set of transmission parameters for a possible uplink channel. Next, SSs perform *Ranging,* to acquire the correct timing offset and power adjustments, and *Authorization and Key exchange*. Subsequently, *Registration* is carried out by a request and reply exchange in order for a SS to become manageable and thus be later able to request a data connection. Once the SS is registered, it is eventually ready to perform *Establishing Connections*. Here, either the BS or the SS requests a service flow creation. A service flow basically defines an association of a transport connection and a specific set of QoS parameters. It is worthwhile mentioning that WiMAX supports transmissions prioritization by employing several scheduling services which specify a set of QoS parameters for real-time and non-real-time connections. At this point, *Bandwidth Request* messages are employed to manage the bandwidth resources according to the demand of the different service flows. Once the whole process is completed, SSs are able to transmit and receive data packets.

2) *WiMAX implementation in iTETRIS*

The ns-3 WiMAX module developed by INRIA [8] has been taken as a base in iTETRIS to elaborate an optimized implementation tailored to fulfill the scalability requirements of the iTETRIS platform. The INRIA implementation module, aimed at providing a standard-compliant simulation model, is notably extensive with respect to the iTETRIS simulation purposes. Since the evaluation of WiMAX system level behavior is out of scope of the project, a high level of detail is not only not required, but it would also prevent us to evaluate WiMAX vehicular communications capabilities in large-scale scenarios. Based on the iTETRIS simulation performance needs, the main objective is to reduce the complexity and accuracy of network management operations. In this context, next table classifies the set of WiMAX functionalities previously described, differentiating between *non-implemented*, *simplistically modeled* and *implemented* functionalities in iTETRIS.

TABLE I. iTETRIS WiMAX FUNCTIONALITIES

Non-implemented	Simplistically modeled	Implemented
Basic capabilities Authorization Time establishment Operational parameters	Scanning & Sync UL parameters obtaining Ranging Burst profile management Registration Establishing connections	Data connections

The standard considers a set of optional functionalities, which in most cases are not fully specified. This group corresponds to the *non-implemented* functionalities in iTETRIS. On the other hand, *implemented* functionalities, concerning the exchange of data traffic between stations via unicast or broadcast transmissions, are accurately modeled with the aim of being standard compliant. Finally, *simplistically modeled* functionalities are mostly related to management and control procedures and have been implemented by introducing some modifications aimed at reducing the computational resources required by network management tasks. The main simplifications are briefly described in the following:

- *Infrastructure location map:* iTETRIS employs a reference map, with the locations of all the BSs, which is periodically consulted by SSs to work out the BS they should be attached to. To reduce computational costs, the *Scanning and synchronization* and the *UL parameters obtaining* functionalities are easily performed by consulting the reference map.

- *AMC reference map*: following a similar approach, an additional reference map is employed to determine the modulation and coding (*burst profile*), and the transmission power to be employed by SSs depending on their distances to the attached BS and the radio channel conditions. An AMC (*Adaptive Modulation & Coding*) model has been created based on link-level performance statistics. This ACM reference map simplifies the *ranging* and *burst profile management* processes avoiding the exchange of messages between SSs and BSs.

- *Command managers*: the management and maintenance of the network has been modeled by means of a set of primitives exchanged between BSs and SSs. Command managers attached to BSs and SSs have been implemented to manage the transfer of control information between the different stations. Therefore, the functionalities *registration* and *establishing connections* are undertaken through the exchange of primitives without the need of transmitting any control packet.

- *PHY layer simplification*: the physical layer implementation has been simplified by introducing PER statistics obtained from WiMAX link-level simulations carried out in Matlab Simulink.

- *Emulation times*: in spite of having simplified many of the management functionalities, the iTETRIS WiMAX model accurately reproduces the delays of network control processes by including emulation times for each management functionality.

C. *UMTS*

Given that iTETRIS specially focuses on the study of radio communications between vehicles, and between vehicles and infrastructure, iTETRIS only implements the radio access network of UMTS, called UTRAN *(UMTS Terrestrial Radio Access Network)* [9], omitting the modeling of the wired communications between the different network entities in the core network.

1) *UMTS operation overview*

UTRAN distinguishes three different kinds of functional nodes: UE (*User Equipment*), Node B and RNC (*Radio Network Controller*). The UE corresponds to the mobile end-user's terminal which interfaces with the user applications and the radio access network. The Node B is equivalent to the GSM base station and thus is in charge of performing the air interface layer 1 processing (channel coding and interleaving, rate adaptation, spreading, etc.) based on the WCDMA (*Wideband Code Division Multiple Access*) technology. Finally, the RNC is the network element responsible for the control of the radio resources of the UTRAN based on QoS specifications. It also performs admission control, connection establishment and maintenance. Different types of channels (*logical*, *transport* and *physical*) are defined to support broadcast and unicast transmission modes, transmissions of control and data information, and assignment of shared or dedicated radio resources to the users. Data transfer modes for transparent, unacknowledged and acknowledged communications are also specified.

2) *UMTS implementation in iTETRIS*

iTETRIS has selected the UMTS module implemented at the University of University of Strathclyde (Glasgow) [10] for developing a modified implementation in the ns-3 simulation platform. Some of the functionalities of the selected implementation have been simplified or even eliminated, owing to the iTETRIS requirements and large-scale constraints. The main modification of the architecture has affected the control plane of the application since all the control messages have been replaced by primitives between the equivalent layers of the communicating nodes. As in the original implementation, two nodes have been developed, UE and Node B. The Node B has acquired the intelligent and functionalities of the RNC in order to reduce the complexity of the communication architecture implementation. Two new NetDevices have been created, one for the UE and the other for the Node B. With the purpose of providing methods to model procedures of the control plane, such as handover or the setup of a new connection, a new element called *UMTS Manager* has been introduced. This entity is in charge of processing the demands related to the control plane. Thus, it stores a pointer to all the Nodes B deployed in the scenario of the simulation. When the *UMTS Manager* receives a petition of any control operation, like a setup request to a certain Node B station, it notifies the demand to the RRC layer of the correspondent Node B and the response is also noticed to the originator UE node.

IV. ITS-G5A Physical Layer Modeling

The research on wireless communication protocols that can be heavily influenced by the radio propagation conditions, such as vehicular geo-networking protocols, need to carefully model the physical layer effects. On the other hand, the scalability constraints of the iTETRIS platform imposed by the large-scale scenarios, require modeling techniques to reduce the simulation complexity and computational costs. To this aim, iTETRIS has adopted the methodology to include the physical layer effects by means of Look-Up Tables (*LUT*), mapping the packet error rate (*PER*) to the experienced channel quality conditions expressed in terms of the effective signal to interference and noise ratio (*SINR*). The link level simulations necessary to obtain such LUTs are being conducted in Matlab Simulink. Given the novelty and difficulty to adequately model the vehicular radio channel, this section presents the iTETRIS ITS-G5A link level implementation and the first performance figures achieved using vehicular radio channels developed by the Georgia Institute of Technology [11].

Since ITS-G5A is based on IEEE 802.11a standard, the implemented physical layer model is an adaptation of the Simulink 802.11a physical model. The fact that ITS-G5A employs a 10Mhz wide channel, instead of the 20Mhz one used in 802.11a, causes that all OFDM timing parameters are doubled. The ITS-G5A block diagram of the transmitter, the vehicular channel and the receiver implemented in Matlab Simulink is depicted in Figure 2. In the transmitter block, the *data scrambler* is responsible for avoiding the appearance of certain data bits sequences with higher probability than others. The *convolutional encoder* is employed for Forward Error Correction (*FEC*) and provides data rates of 1/2, 2/3 and 3/4. The *data interleaver* block is aimed at mitigating the impact of burst errors. After the interleaver block, the *modulator* supports the BPSK, QPSK, 16-QAM and 64-QAM modulations. The modulated data is then mapped into 48 different subcarriers. After inserting 4 subcarriers as pilots, the OFDM symbol is composed, consisting of 52 subcarriers in total. In this block, training symbols are inserted at the beginning of the frame and will be used by the receiver for channel estimation and fine frequency acquisition. For each group of subcarriers, or OFDM symbol, the IFFT block converts the subcarriers into time domain using inverse Fourier transform. Finally in the transmitter, the Fourier-transformed waveform is appended with a guard interval, aimed at avoiding inter-symbol interference caused by multipath effect.

Given the high variability of the wireless vehicular radio channel, one key block in the receiver is the *channel estimator and equalizer*. The channel estimator implemented employs the OFDM training symbols transmitted at the beginning of the OFDM frame to estimate the channel response using the LS algorithm. In conventional channel estimation, it is assumed that the channel exhibits time-invariant fading, and thus can be approximated by the channel response estimated with the training symbols for the whole packet duration. However, in fast varying channels such as the vehicular channel, it has been shown that the channel response considerably varies during the packet duration and thus its estimation must be performed on a symbol by symbol basis [12]. Consequently, the equalization process of a given OFDM symbol is made based on the channel response estimation of the previous one (feedback decision). In order to obtain low boundaries figures on the PER and BER performance curves, an ideal channel estimation of each OFDM symbol, considering that the transmitted symbols are perfectly known at the receiver, has been assumed in this work.

The vehicular channel characterization exhibits important differences with conventional cellular systems due to the transmitting and receiving antenna heights (in particular for V2V communications), the varying propagation conditions and the high mobility of nodes and scatters [13]. In this context, there are currently considerable research efforts focused on developing V2V channel models [11][14]. Based on a preliminary comparison study on vehicular channel models, iTETRIS has selected the set of channels developed by the Georgia Institute of Technology [11] to be used in the link-level performance characterization of the ITS-G5A physical layer. The decision on the choice of the Georgia channel

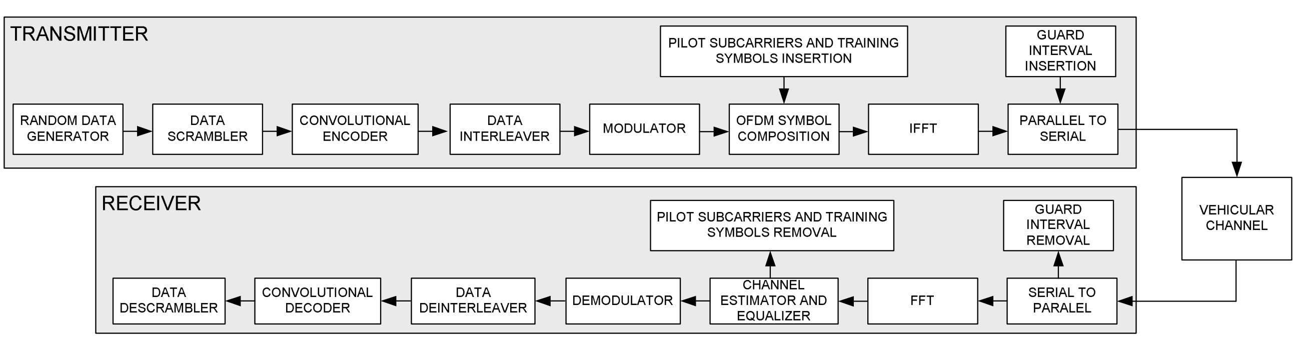

Figure 2. *ITS-G5A PHY layer block diagram.*

models has been influenced by the fact that they were generated to be employed for WAVE equipment certification tests. These channels provide V2V and V2I models based on measurements at 5.9GHz. The type of model considered is the tapped-delay line, where each tap process represents a multipath component and is described as having Rician or Rayleigh fading and by a Doppler spectrum. The next figures show the first ITS-G5A BER (*Bit Error Rate*) and PER link level results obtained in iTETRIS for a packet size of 100 bytes and using soft-Viterbi decoder. The figures have been obtained for the Georgia Tech *V2V Expressway Oncoming* channel model. This model reproduces a highway scenario where two vehicles are driving in opposite directions at 105km/h. The separation distance between vehicles is approximately 300-400 m.

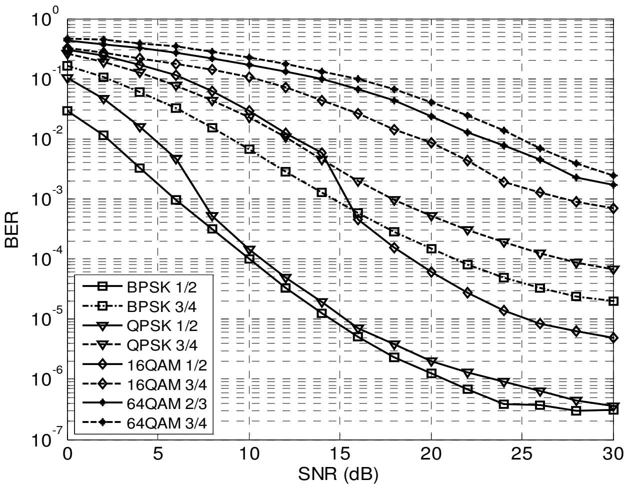

Figure 3. *BER performance for "V2V Expressway Oncoming" channel.*

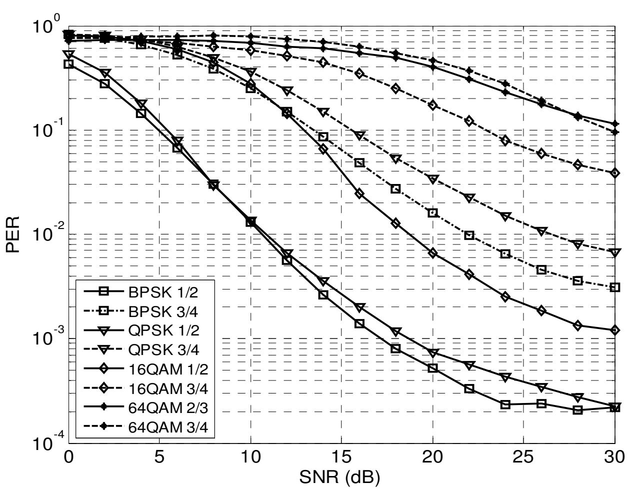

Figure 4. *PER performance for "V2V Expressway Oncoming" channel.*

V. CONCLUSIONS

This paper has presented the iTETRIS heterogeneous wireless simulation platform that is being developed with the main objective of meeting the existing need to demonstrate the large-scale impact of cooperative technologies on traffic management. The iTETRIS platform will allow investigating V2V and V2I communications in multi-technology environments as well as their potential to improve traffic management. In this paper, platform design aspects essential to conduct computationally efficient large-scale simulations have also been considered, providing implementation details devoted to reduce the complexity of the communication modules (ITS-G5, WiMAX and UMTS). Given the importance of realistically modeling the radio communication link in simulation research, this paper has also focused on the ITS-G5A PHY layer characterization and has presented BER and PER performance curves for V2V communications in highway scenarios.

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