POLITECNICO DI TORINO

SCUOLA DI DOTTORATO
Ph.D. Course in Electronics and Telecommunications – XXVII cycle

Ph.D. Dissertation

Analysis, simulation and testing of ITS applications based on wireless communication technologies

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March 2015

Summary

Intelligent Transportation Systems (ITS) aim to improve road transport safety and efficiency, to manage road networks in the interest of the society and to provide real time responses to events. In order to reach these goals, real time feedback to the drivers is expected through the integration of telecommunications, sensing and information technologies with transport engineering. Wireless communication technologies, that have been used in industrial applications for more than 30 years, play a crucial role in ITS, as based on the concept of multiple devices (on both vehicle and infrastructure side) interconnected in different ways.

Connectivity, in tandem with sensing technologies, is fuelling the innovations that will inevitably lead to the next big opportunity for road transport: autonomous vehicles.

Therefore, this study has investigated - through analysis, simulation and field testing on applications based on wireless communication technologies meant to support both Data acquisition and Data diffusion as fundamental aspects/ phases in ITS, where data is widely individuated as being the key element.

Acknowledgements

I would like to thank my advisor Prof. Guido Albertengo together with the whole TNG group at the Politecnico di Torino for their support in this challenging experience.

I would like to thank my Intership Advisors Ing. Domenico Zagari and Ing. Gino Franco for allowing me to grab this opportunity, and for making available all necessary technical (and moral) elements during the last three years.

I would also like to thank the team of Prof. Fritz Busch for their hospitality during my short stay in Technical University of Munich and for their great work in the field of C-ITS Simulations.

Finally, I would like to thank my family, especially my son Davide, for standing there for me all the way through - without whom would have been impossible reaching this goal.

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Chapter 1

Introduction

This PhD activity is based on the link between research community and industry as it raises on the bases of the collaboration between Politecnico di Torino, SISTRA and mother company SWARCO MIZAR. The research activity has been performed on application level, focusing on these two companies activities within R&D (Research and Development) EC-funded projects, in order to: (a) bring academic know-how into industry by contributing to the design, development and test of usable innovative ITS (Intelligent Transport Systems) solutions and (b) train the student for the integration in an international research context.

The research context for this PhD thesis is what today is being called ITS, specifically addressing road transport. New infrastructures cannot solve congestion and emissions problems due to high traffic intensity, but ITS, applying telematics to transport, can provide new services, able to reduce congestion and pollution, without building new infrastructures or expanding existing ones [1]. Although the effectiveness of ITS strategies in improving many kind of transport systems had been widely analysed and proved by the scientific community, most proposals never became real systems due to the lack of adequate infrastructure monitoring technologies: most ITS applications require information in real-time and with high quality and high resolution.

Connectivity, in tandem with sensing technologies, is also fuelling the innovations that will inevitably lead to the next big opportunity: autonomous vehicles. Therefore, this thesis has investigated - through analysis, simulation and field testing on applications based on wireless communication technologies meant to support both Data acquisition and Data diffusion as fundamental aspects/ phases in ITS, where data is widely individuated as being the key element.

Research activity during the PhD period was concentrated on these two complementary aspects of ITS: Data acquisition and Data diffusion.

A first part was focused on WSN for Road Infrastructure Monitoring. SISTRA has deployed a prototype system designed for road side applications based on an advanced radio protocol in ISM band (2.4 GHz) for linear topology WSN. The research activity was focused on the analysis and validation of the proposed scheme, in relation to three applications: indoor localization in road tunnels, traffic monitoring in highway environments and intelligent public street lighting in urban areas. These activities are described in the first chapter of the thesis.

The second chapter addresses a complementary aspect in ITS: I2V Communication for the provision of Traffic Light Assistant service. SWARCO MIZAR provides TLA (Traffic Light Assistant) service in three European cities (Verona, Garmisch and Berlin) and is heading towards large scale deployment. The students research activity was focused on the realization of a simulation tool-kit meant to support the design phase for TLA solutions.

Finally, conclusions on this research experience close the document.

Chapter 2

WSN for Road Infrastructure Monitoring

2.1 Introduction

Even though the efficacy of ITS strategies for improving comfort, safety and efficiency of road transport has been widely analyzed and proved by the scientific community, most of them have not been implemented in practical systems because of the lack of adequate traffic monitoring technologies, mainly due to high deployment costs and limitations related to complex installation process [2] [3].

Traffic data collection systems are essential tools for real-time ITS applications, such as adaptive intersection control, routing and traffic information services. Even if new trends for traffic data collection like tracking data from cellular networks or GPS raised the interest of the transport community as a feasible low-cost alternative to traditional technologies (i.e. inductive coils) major drawbacks as accuracy and reliability characterize these technologies and therefore are meant to complement and not replace conventional ones. WSN represent a breakthrough technology for traffic monitoring as it combines low-cost autonomous sensing devices with scalable self-configuring wireless networking [4] .

This chapter introduces RED-WINE [5], a multi-sensor system that aims to provide a solution for generating automatically safety warnings at black spots by using traffic-related data acquired on the road network. The system features three main characteristics - (i)low power, (ii)low cost and (iii)low maintenance - combination that represents the strength of RED-WINE respect to other existing solutions (e.g. magnetometers based systems).

The system, made up of sets of nodes installed on the roadside is able to provide an integrated solution for road infrastructure monitoring with following features:

crash and barrier tilt detection, traffic status detection (occupancy variations), monitoring of environmental parameters (i.e. ice warnings), WWD detection, indoor localization on road axis (adapted for tunnels or bridges) and colour-coded signalling (luminous wave and on/off flash). The node (called GRAPE), composed by an acquisition module, a communication module and a power-supply module, is the RED-WINE core element.

An isolated solution, called IEDG is available when local event detection is desired in a critical point of the roadside and it is already a commercial product. The know-how derived from IEDG long-term installations (50 devices installed on interurban roads for traffic monitoring, crash detection and ice warning) lead to the design and development of the distributed solution, called WEDG, described in this chapter.

An advanced wireless communication protocol in 2.4GHz ISM band has been designed and implemented in order to permit communication among a large number of nodes, taking advantage of the linear topology of the network, typical for roadside applications. The wireless connectivity reduces the cost of installation and maintenance with respect to the existing monitoring technologies and, at the same time, offers a much greater flexibility of deployment, providing a comprehensive and high-resolution sampling of traffic variables, that permit, on centre side, to reconstruct the spatialtemporal evolution of traffic flows and localise any detected anomaly along the road [6].

Various solutions were tested inside the laboratory and on the field, and the system was involved also in international contexts within eu-founded project experiments, in various applications, implementing network configurations from 3 to 10 nodes: localization of mobile node in tunnel environments (Terni, SAVEME EC-funded project, 2012), intelligent street lighting (Salerno University, COSMO EC-funded project, 2012-2013), level of service individuation in a highway environment (Vienna-Graz Highway, COSMO EC-funded project, 2011-2012).

The remainder of this chapter is structured as follows: a first section proposes an overview on RED-WINE system and its networking solution by describing the dedicated MAC protocol, the prototype and some basic performance considerations. The following sections are dedicated to the three applications that were mentioned in the previous paragraph, illustrating for each one of them the motivation and related work, followed by a description of the realized field tests with correspondent results.

2.2 A Linear WSN for Road Infrastructure Monitoring

2.2.1 Application requirements

WSN are constantly increasing their presence in many application fields. The common sense would suggest a single network architecture able to cover all application areas, as in the case of the Internet/Intranet protocol stack. However, the requirements of the applications operating on each WSN are very different from each other, as in some case also is the network topology. This led to a large number of different protocols ranging from the data-link layer up to the transport layer, each with the goal to perform optimally in accordance with the applications required quality of service and with other commercial and technical requirements [7].

Most recent trends in ITS involve the use of WSN for road infrastructure monitoring. There are present in literature various solutions for such systems based on several sensor technologies and network approaches:

1. Sensor technologies

- Anisotropic Magneto-Resistance (AMR) sensors
- Acoustic Sensors
- Passive Infrared (PIR) Sensors
- Accelerometers
- Piezoelectric Sensors
- Microwave Radar
- Video Image Detection

Parameters like desired functionality, precision, detection range, encapsulation needs and power consumption influence the choice of sensing subsystem for data acquisition.

2. Network approaches

- Topologies
  - String and cluster string
  - Mesh
  - Star
  - Disconnected nodes

  - Vehicular sensing

- Architectures
  - Flat
  - Multitier
  - Heterogeneous

- MAC Communication protocols [26]
  - Unscheduled or random protocols
  - Scheduled protocols
  - Contention based (use Carrier Sense Multiple Access (CSMA) techniques)
  - Contention-less (use Time Division Multiple Access (TDMA) techniques)
  - Hybrid protocols

Main network technologies described above are mentioned in [25] , along with main applications of WSN-based ITS that are present in literature:

- Traffic safety applications;
- Traffic law enforcement applications;
- Traffic control applications;
- Smart parking applications.

Therefore, in our area of interest, i.e. RTT, as well as in many other areas related to infrastructures, the concept of intelligent infrastructure, which includes infrastructures with an embedded WSN, is a high-interest topic for both research and industry. A major advantage of this approach is that the WSN can even be added to existing infrastructures, enhancing their usage and performance, with a limited economical investment.

RTT has leveraged on intelligent systems to increase traffic fluidity and to reduce the accident rate since some 30 years. Current RTT solutions collect traffic measures and events (congestions, accidents, roadworks, ..), validate and process them on a central site, the TCC, and finally inform drivers through radio broadcasting or VMS. Traffic measures and events are now mostly collected using inductive loops and cameras, but new types of roadside sensors are on field tests. These sensor can not only identify the traffic intensity, but also detect congestions and even crashes occurring on a road using a large number of sensor nodes deployed along the road, at distances ranging from 50 to 100 meters from each other, forming a linear topology sensor network. To minimize the cost of the systems, nodes are solar or battery powered, and a radio system is used for communicating: the resulting network is therefore a Linear Topology WSN, or LT-WSN.

The low energy consumption, as well as the low latency required by this LT-WSN, make all currently available protocols for WSN unusable. Thus, a new protocol in the ISM 2.4 GHz band for a LT-WSN with low latency and low energy consumption had to be designed and implemented.

LT-WSN have already been investigated and some results are already available in the literature (i.e. LEACH, PEGASIS, APTEEN), but in general the focus was so far on energy efficiency [8] [9] [10], always neglecting crucial aspects for our application field, such as low latency, network reliability, high density of the sensors and synchronization [11].

Moreover, this network should cover some kilometres of road with sensor nodes deployed every some 50 m on the roadside, with just two gateways at both ends of the sensors chain: the resulting number of sensors in a single LT-WSN is thus in the order of the hundreds (5 km can be covered by 100 sensors at a distance of 50 m).

The proposed LT-WSN must therefore be based on multi-hop transmission with a very high number of relay nodes, and consequently a potentially very high latency. Furthermore, since the proposed network operates in the 2.4 GHz ISM band, the interferences with other systems operating in this same band must be taken into account. Finally, energy consumption must be minimized, to increase the duration of the batteries, or to reduce the size of the solar cell. After having identified a candidate device, the TI CC2510 [12] , selected for its low energy consumption, possible interferences were analyzed, then an energy-efficient and low latency Data Link Layer Protocol was designed.

2.2.2 A dedicated MAC scheme

Interferences study in ISM band (2.4 GHz) for the CC2510

The transmission system is formed by a CC2510 and a CC2590. The integrated radio device CC2510 operates in the ISM band at 2.4 GHz, can be tuned on one out of 80 channels , and uses one out of these classic digital modulation schemes:

- 2-FSK
- GFSK, filtered with a Gaussian filter in order to reduce power in the narrow bands
- MSK

The maximum transmission speed, as indicated in the device data-sheet is 500KBaud which corresponds to a data rate of 500Kbit/s for FSK and MSK modulations while it is only 250 kbps in case of GFSK . The bit error probability at the receiver is however different for each of these two modulation schemes: being the receiver identical for both of them, MSK performs better than FSK, since it uses less bandwidth. Hence, MSK modulation has been selected in the proposed system. The interference with other systems operating in the same ISM band, independently of the modulation technique they use must be carefully considered, since it could be major source of packet losses. In particular, Wireless LAN, such as WiFi, and Bluetooth are the two most diffused systems in this ISM band: the first uses a DSSS modulation, whereas the latter uses a FHSS modulation. As a consequence, WiFi will just be a source of some additive noise for our receivers, and the countermeasure is simple: avoid using channels with low SNR. For Bluetooth, the situation is more critical: both our system and Bluetooth use the same channels, and the same modulation schemes, so that interference is maximum and unavoidable. The solution we envisaged uses packet duplication to overcome the problem. Since any type of radio signal can be emitted in ISM bands, just keeping it within the limits specified for the band, other radio sources could produce some interferences: we counteract as in the case of WiFi, changing the radio channel as soon as its SNR or its PLR). Summarizing, in order to limit the effect of all sources, but Bluetooth, it was decided to:

- Associate a single transmission channel, selected among the 80 available, to every node
- Measure in every node the SNR on all 80 channels
- Change the node transmission channel whenever its PLR becomes too high, using a high SNR channel as the new transmission channel

For Bluetooth, since any countermeasure at the radio channel layer is unfeasible, we leverage on the FHSS modulation used by Bluetooth, that makes the subsequent transmission of the same packet, lasting no more than a Bluetooth slot time, onto two different channels very unlikely to be disturbed by a single Bluetooth source, to build a recovery mechanism at the radio packet layer, as described in the following chapter.

Radio Link sub layer

The wireless nodes will receive and re-transmit PDU that at interface level are referred in this paper as RP. The RP complies with following indications: (i) programmable (and variable) length, (ii) use of CRC for error detection, (iii) Data Whitening option enabled, (iv) length of synchronism set at maximum value (4 byte), (v) maximum length chosen in order to minimize effects of Bluetooth interference and (vi) no use of FEC. In our network, RL level addresses are not used in order to identify the receiver of a RP, but the sender of a RP in order for the receivers to precisely identify the sender. This implies that RL level addresses (RL_ADDR) are unique and unchangeable. As indicated, the mechanism for filtering addresses is disabled, that leaves 256 available addresses (from 0x00 to 0xFF). The addresses respect the following rules: (i) the addresses are statically assigned; one node never changes address, (ii) in every chain all nodes must have a different address and (iii) in two adjacent chains, where in case of damages the two chains merge in one unique chain, the nodes must have different addresses. Six less significant bits of the node address (NODE_ADDR) are used in order to uniquely identify a node inside a chain, and the 2 most significant bits in order to identify the chain (CHAIN_ADDR). 0x3F indicates that a node has no assigned address (in this case the CHAIN_ADDR value is non influential).

In order to minimize the effect of Bluetooth interferences the best choice is to use identical (or at least very near) radio channels (carrier frequencies) as those utilized by Bluetooth. By using the CC2510 component this becomes possible, and 79 radio channels are realized that will be indicated as RL_CHAN and will be numbered from 1 to 79. (The value 0 indicates an unknown channel.) Given the fact that the major identified packet loss cause is the Bluetooth interference, the dimension of one RP needs to be optimised respect to the duration of a Bluetooth packet, equal to a slot (625 s value determined by a hopping frequency of 1600Hz) as the minimization of the effects of Bluetooth interference is obtained when maximum duration of a RP is equal to the duration of a Bluetooth transmission. The loss probability of the RP, always conditioned by the fact that a Bluetooth transmitter should be active, would be equal to 2/79 = 2,53%. If a major efficiency due to band use is desired, using longer payloads it will be a correspondent increasing of the loss probability due to Bluetooth interference; therefore the RP duration should be a multiple of Bluetooth slot duration, in order to have a maximum RP length at equal loss probability. Functions at this level are four:

- Timing generation: realized only by the Gateway node; the access control system uses a TDMA technique, it is necessary having an unique timing reference point within the whole chain, in order guarantee the fact that in any moment there arent nodes that might create disturb doe each other due to the contemporary use of the same channel; timing base is generated using a hardware counter, within the CC2510 is called the MAC Timer - the gateway generates with the period BCN_PERIOD a BEACON message that will be received by every node inside the chain with a delay that depends only on nodes position.

- Timing recovery: this function is present in all nodes except the gateway. Every node receives every BCN_PERIOD a message called BEACON. The value of BCN_PERIOD is measurable and determined by the gateway: the BEACON reaches every node in the chain with a delay approximately constant respect to the gateway, delay that depends on nodes position and on BEACONs length. In order to completely recover the synchronization, every node must acquire BEACONs periodicity, and also characterising parameters for the chain.

- Transmission: this function is being executed by all nodes. One message is being segmented in order to permit the transmission through a sequence of consecutive slot with a RP number equal to slot numbers. After the segmentation one or more RP are ready for the transmission of length not necessarily constant and the first RP is transmitted in conjunction with the start of the first slot dedicated for the transmission, while the eventual following RP are being successively transmitted, separated by headers. The CC2510 operates in this way by programming the field MCSM1.TXOFF_MODEL[1:0]=10 if after the current RP follows another RP and MCSM1.TXOFF_MODEL[1:0]=00 for the last RP.

- Reception: this function is being executed by all nodes. The transmission mode for a sequence of one or more RP requires the receiver setting in order to receive more RP in sequence. The number of RP to be received is known by the access control system and is equal to the number of slots reserved for message transmission. The receiver must be ready for reception at the beginning of the first slot; the radio device must be activated with a sufficient advance in order to give the time for a fully operative state. The effective time depends on the programmed mode of the receivers VCO, and is always less than 800 s (correspondent value of a complete calibration). In the case when RP_CRC control is not passed, the RP is being memorized anyway, but error presence is signalled by the flag called RP_CRC_OK set at FALSE value.

Access Control sub-layer

This sublevel deals with the access at the transmission channel, by activating the Radio Link level in transmission and reception mode at the suitable time and using the suitable radio channel. This sublevel has also other functions: message forwarding, command reception and event transmission. Its suitable defining a series of terms that will be used in order to describe the access protocol:

- NODE: a device able to receive and transmit through the radio channel con at least other two nodes

- CHAIN: a sequence of CHAIN_LEN nodes disposed at regular distances and in a ordered succession, that form a topology equivalent to an active bus

- POSITION: progressive number that indicates the position of the node inside the chain. The first node of a chain will be in 0 position and the last in position CHAIN_LEN 1, in a chain of CHAIN_LEN devices (gateway included)
- GATEWAY: node in position 0 in one chain
- TERMINATOR: the last node of a chain (but not necessarily the one in position CHAIN_LEN-1 in the case when the chain is not complete)
- DOWNLINK: node sequence from gateway to terminator
- UPLINK: node sequence from terminator to gateway
- MESSAGE: a set of structured information
- SEGMENT: part of a message of such dimension that is completely contained within a RP
- SLOT: time interval that represents the time unit for the chain. In one slot is possible transmitting one RP.

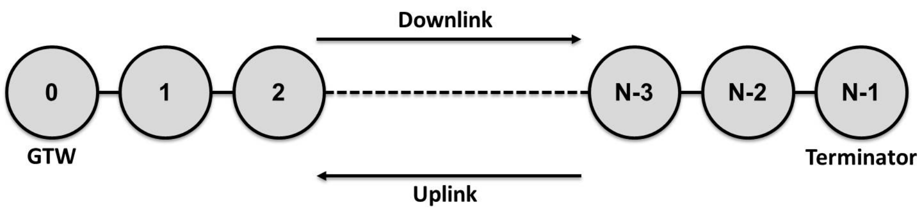

Figure 2.1. Chain structure

NETWORK TOPOLOGY Within the network chain, the radio signal range of every single node is not enough in order to reach all nodes, but only certain nodes disposed in the neighbourhood; reaching the other nodes depends on propagation conditions, node distance and also other factors. Therefore, it will be assumed that one can, in normal operating conditions, transmit and receive from 4 distinct nodes: the previous 2 nodes and the 2 nodes in succession (e.g. for node i: nodes i-2, i-1, i+1, i+2) realizing 2 logical paths for network information, called downlink when information travels from gateway to terminator and uplink when information travels from terminator to gateway. The logic topology is realized with an AFB, that was already extensively used, even with passive nodes, for experimental networks. The most simpler access mode that permits realizing this type of transfer (the nodes will first receive information from one node upstream and will transmit it at a predetermined time downstream) is TDMA, that ensures that only one node at the time can use the radio channel, avoiding in this way simultaneous transmissions. Furthermore, in this case, given the high availability of different radio channels (79) its suitable using a mixed technique TDMA-FDMA, in order to permit simultaneous transmission of nodes that use different channels. Besides the TDMA_FDMA system mentioned, the sublevel AC realizes also a DAMA protocol that permits the variation of the band assigned to every node on uplink. Every node inside the chain is characterised by an AC level address, that will be called NODE_ID, coded on 1 byte. On contrary, RL level address (RL_ADDR), that is set in installation phase and indicates the spatial position of the node within the segment between 2 gateways, NODE_ID only indicates the position within the logical chain, managed by a gateway and can vary if the logic chain varies.

MESSAGE MANAGEMENT The messages are the data units of the AC sublevel protocol. There are present following types of messages:

- BEACON: is generated by the gateway and propagates along the downlink: is used in order to synchronize the nodes from the chain and to transport the commands toward the nodes
- EMERGENCY_BEACON : used instead of the beacon when the chain is interrupted
- CAR: generated by the terminator and propagates along the uplink: is used in order to collect data from the nodes and transport it towards the gateway
- P2P: used during the connection between a node in the chain and an external node in order to establish a point-to-point connection between them for data transportation

The dimension of a message (MSG_SIZE) its not constant and varies from a minimum of 2 bytes (its header) at a maximum of 4096 bytes. The field MSG_TYPE identifies message type and permits distinguishing between various types of message. The field MSG_NUM is the progressive number of the message, where used, or a pre-determined code. The field MSG_CHECK is the check sum of the control fields (MSG_TYPE, MSG_NUM and MSG_CNTRL), realised as the sum mod 16 of groups of 4 bit. The field MSG_CNTRL contains the specific information from the 2 types of messages BEACON and CAR and has a dimension equal to BCN_CNTRL_LEN or CAR_CNTRL_LEN respectively.

Within the field MSG_DATA there are situated the IU:

- commands: when they are used in order to send nodes commands for chain control. The commands (CMD) are created by the gateway and transported along the downlink over the chain nodes. Commands length is variable, but the same structure, reported in the figure below. All field occupy more or less one byte. The fields that have 0 length may not be present.

- confirmations: when they are used in order to transport collected data from nodes to gateway. The UI that only transport a feedback information for a received command are being called acknowledgements.

- data: when they are used to confirm receiving a command without any other associated data. The UI that contain information generated by the nodes present in the chain are called data. Those have a common format, presented in figure below. Data can be sent either in access without reservation mode (RES_ID=0) or in a reservation mode (RES_ID contains the reservation number used for the transmission). In the last case the total dimension DATA_SIZE of a data should never exceed the byte number (IU_SIZE) request within the reservation, but can be inferior.

The events are signals for the GTW regarding changes of the nodes state or the monitored environment. Within the system described in this chapter there is the possibility to fragment a message in more segments, each one of them being transported by a RP. The segmentation has the scope to reduce the information loss probability, by transmitting an informative block that is not totally contained within a RP through a sequence of radio packets independent and consecutive, every one of them having a very small size. If the loss probability is enough low, larger radio packets should be created in order to avoid segmentation. The choice depends on operative conditions. Contrary, all messages that travel on the channel are segmented, even if they occupy, together with the segmentation bytes, only one RP. If a node adds to a message one or more UI, will also add enough segments as necessary, leaving unchanged the segments not modified by the insertion, except the field that indicates the total number of segments (maximum 16). The message reconstruction is a twophase function ((i)segment confront and (ii) message reconstruction) realized by all nodes and aims to take advantage of the fact that every node within the chain can communicate both with the adjacent nodes (one node distance) and the adjacent of the adjacent nodes (2 nodes distance). During the receiving phase a node receives 2 segmented messages, one from 2 distance node and one from 1 distance node. In every one of the 2 messages there might be the same information, like for the BEACON messages, or only partially the same, as for the CAR type messages.

ACCESS CONTROL The access control defines the timing mode, the timings that nodes use in order to access the channel and the transmission procedure of data to the GTW and the scope of access control is:

- Realize the logic topology
- Permit the propagation of an unique BEACON for every cycle
- Permit the propagation of multiple CAR for every cycle
- Permits the transmission to the GTW the data generated by the nodes

In order the reach the first 3 goals, there has been adopted a choice that, without losing the obtainable performances, permits simplifying the operations that the nodes need to perform: all channel access operations take place periodically: the BEACON, that propagates downlink, needs to occupy a constant number of BCN_SLOTS, as the single CAR needs to occupy always CAR_SLOTS along the uplink. A slot is needed in order to transmit a segment, so the slots number equals the segment number. In order to reach the last scope, it has been chosen to join 2 different data send techniques: the first a non deterministic one, suitable for asynchronous UI transmissions, the other deterministic one, suitable for the transmission of periodical IU and large data quantities. On downlink travel BEACON type messages, that have maximum length MAX_BCN_SIZE. A node expecting the BEACON will be tuned in reception mode on the channel NODE_CHAN(NODE_ID-2), that is the channel associated to the node on uplink at distance 2 at time BCN_RX2 and it will receive the first copy of BEACON. Then the node will be tuned in reception on channel NODE_CHAN(NODE_ID-1) that is the channel used by the node on uplink at distance 1 and will receive the second copy of BEACON. The GTW has associated 2 transmission channels: the first one (NODE_CHAN(-1)) used to transmit the first copy of BEACON and the second (NODE_CHAN(0)) for the second BEACON copy. For both BEACON copies sent by the GTW, both RL level address RL_ADDR as MAC level address NODE_ID are identical and the first node in the chain must consider this issue in order to maintain the exact synchronization. The effective arrival timings of the 2 BEACON are also used to correct, if necessary, the SYS_TIME value (the timing correction is being performed by the RL sublevel operating on the timer, as described in section 1.5). For the correction are being used both RL level address and MAC level address of the sender, the first one available at RL level and the second directly readable within the BEACON, that permit to exactly know the position of the nodes uplink and recover the correct value of SYS_TIME. The node proceeds to BEACON reconstruction, to the decoding of eventual commands contained by the BEACON and retransmission of the BEACON downlink. If the node is able to partially reconstruct the BEACON, sends the constructed part, if it results unable to reconstruct any part of the BEACON sends an empty BEACON in order to maintain the synchronism with the node downlink. The GTW has a superior switching on time, given the fact that transmits 2 copies of the BEACON and then switches to listen mode, but the GTW is not battery supplied so this does not represent an inconvenient. Along the uplink are traveling from 1 up to CAR_NUM CAR messages that succeed in time at constant distances. The CAR form a TRAIN that starting from the terminator reaches the gateway transporting the various CAR generated by the nodes. Here also is being realized a TDMA system for the access control together with suitable channel assignment in order to avoid interference between 2 nodes in the same range that transmit in the same time. The CAR sequence that travels on uplink is started by the terminator, that at the end of timing for downlink management (that concludes at time BCN_DURATION) starts generating the first CAR. Every node inside the chain, in order to realize the transmission on uplink, receives starting from CAR_RX1 the first copy of the message, that is transmitted by node at distance 2 upstream on uplink, then at time CAR_RX2 receives the second copy, transmitted by the node at distance 1 upstream on uplink, combines the 2 messages by operating eventual corrections and adding the transmitting data and then at time CAR_TX starts the transmission time. Concluded the transmission period, restarts with the reception of the first copy of the successive CAR, performing again the cycle described above. The node continues the operations until has the data for the transmission or receives from at least of the 2 nodes a CAR. The node concludes anyway the access operations to the uplink after MAX_CAR_NUM volte, in order to permit transferring all possible CAR in a TRAIN, without exceeding the maximum cycle time. In the case that no CAR reaches the node during the 2 reception periods of a cycle, the node generates a new CAR in the two cases: (i) not all CAR messages with reservation transited and (ii) all CAR messages with reservation transited, but the node has at least one IU not reserved to transmit. In the first case the node creates a CAR with the correct CAR_ID and with CAR_RES equal to the value indicated by the gateway in the description CAR_DESC of the CAR itself, then performs the procedure of inserting the IU, with or without reservation. In this way a CAR is being re-created, identically to the one that would have generated the terminator, that guarantees that all IU reserved for that CAR by the nodes on uplink can be charged on the CAR itself. In the second case, if there have not been MAC_CAR_NUM_CAR transits, the node creates a CAR with the correct CAR_ID and CAR_RES = 0, then performs the procedure on UI insertion without reservation (the ones with reservation were already inserted in precedent CAR messages). All timings are connected to BEACON periodicity (BCN_PERIOD), to the number of BEACON slot (BCN_SLOTS) and to the number of slots of every CAR (CAR_SLOTS). These 3 values, together with MAX_CAR_NUM deriving from it, are parameters that do not vary in a network, but can be chosen in design phase in order to realize networks in different environments. Every node can generate data that needs to be forwarded to the gateway by insertion in one CAR. The data may be available periodically or in an asynchronous way, in function of the generating event. From the logic topology of the network, the most simpler method to send an IU to the gateway is appending it to other IU already present in the TRAIN finding a CAR with enough free bytes to contain it. In order to avoid this problem, there are two possible solutions: (i) limit the byte number to be inserted in every one of the nodes, in function of the TRAIN dimension and (ii) reserve a certain byte number in a certain CAR numbers of the TRAIN. The band reservation mechanism that manages band allocation in the network described in this paper is DAMA type, method that is widely used for satellite access from the earth terminals. The satellite role is assumed by the gateway (the sequence names, uplink and downlink is inspired from satellite system) that receives from the nodes band requests and distributes to the nodes the decided allocations.

NETWORK MAINTENANCE The network maintenance operations are particularly critical, as might change the timings, essential for the correct functioning of the network. For this reason, every time is possible already acquired timings will be maintained and timings will be modified only if absolutely necessary. By analyzing the various cases that need maintenance intervention, following situations have been individuated: (i) installation of a node in addition to the chain, (ii) installation of a node replacing a damaged node and (iii) chain reconfiguring due to gateway connection interruption. All these operations request gateway and nodes cooperation. In particular, the functioning nodes in a chain must detect any state change in adjacent nodes, and communicate them to the gateway, both during insertion of new nodes phase as in order to detect malfunctioning. The installation procedure of a node takes advantage of the presence of adjacent nodes in order to permit the insertion of a new node with a simple intervention of the installation operator. In order to permit chain construction assign the correct RL_ADDR values it is necessary to be predisposed, for every chain, a table called NODE_TABLE that describes the chain itself. NODE_TABLE is composed by rows that contain the following information: (i) NODE_GPS, the geographical localization of the node, (ii) RL_ADDR, the RL level address and (iii) CIC, the unique identification code of the node. In BEACON_MODE modality, the terminal does not transmit the BEACON only in the 2 slots preceding the arrival of the BEACON from the gateway, in the 2 slots succeeding the arrival of the BEACON from the gateway and during the CAR generation period, that depends on the commands received from the gateway. A node that has been switched on for the first time, and does not have a RL_ADDR (indicated by the fact that the field NODE_ADDR=0x3f), performs the following list of actions:

- Channel listening in order to identify active chains

- Link creation with intermediary node or gateway
- Authentication (optionally)
- Node insertion or procedure restart

A configured node, even of just configured by following the procedure described above or already active within the chain but lost the contact due to power supply issues, temporary damage or radio channels issues, in order to couple with the belonging chain needs to follow a ordinate sequence of operations:

- Recover chain timing
- Insert into the chain
- Confirm the presence inside the chain

In the case it results necessary substituting one or more nodes from an existing chain, the procedure is similar to the one described before, but more simpler from the point of view of data management. This is the case when nodes need to be inserted one by one without modifying the chain, so the gateway will not need to send any CONFIG command to the existent nodes but only to the new one, given the fact that will assign it the same parameters (RL_ADDR, NODE_ID, RL_CHAN) of the previous operating node in the same position. The reorganization of 2 adjacent chains, where nodes succeed without continuity solution, consists in shorten the damaged one, and extend the other one by adding the isolated nodes from the first one. That permits recovering, in one chain a damage that involves 2 adjacent nodes, the isolated group of nodes downstream on downlink. In case of node damage, one part of the chain itself the one that starts from the gateway and finishes with the interruption, will continue functioning correctly, while the other part will remain isolated, totally if the first case is verified and partially if one of the other cases is verified. The procedure of reorganizing the survived chain is being started by the gateway, in the moment when recognizes a broken chain. This event is signaled by the node that are positioned downstream on uplink respect to the interruption, that dont receive anymore CAR messages from nodes upstream. On uplink every node is forced to send at least the first CAR of the TRAIN, even if it has no data to transmit, in order to permit the interruption detection. The gateway, once received the notifications NODE_STATUS that identify the possible chain broke, performs a series of operations, reported in figure below:

- Monitoring of the nodes declared broken in order to verify the effective unavailability

- Reorganizing the survived chain
- Notification of the necessity to couple the isolated section from another chain

The GTW sends a command SET_TERMINATOR to the last functioning node that becomes the new terminator of the chain and simultaneously informs the control centre about the interruption event, in order to permit the start of the coupling procedure of the isolated nodes to the adjacent chain.

2.2.3 Considerations on network performances

In order to guarantee the transfer of control messages, the scheme as described in previous sections proposes a double wave of messages: one from the GTW to the terminal that transports commands, and one from the terminal to the GTW that transfers data. That does not only guarantee a limited power consumption, but also ensures the delivery of control messages with guaranteed maximum delays. As noticed, the first wave (commands from GTW to the nodes), is being realized with a distributed TDM technique: every node transmits information received from previous node after a fixed constant time period. A mathematical analysis of network performance has been performed, considering the typical installation of 50 nodes. In the worst case the duty cycle for commands is equal to 0.5% and medium power consumption is equal to 100 uA. The necessary time for a complete data transfer from the sensor nodes to the GTW along a sub-chain of N/2 = 25 nodes is equal to 325 ms, while it is cca 1s for a 50 nodes network. The power consumption depends from node to node, furthermore, the node that is closest to the GTW will spend more energy as it represents the point transited by all information and all commands. In the hypothesis having a chain with N nodes, the number F of MAC_PDU that the last node needs to transmit will be superior to N/10. (every MAC_PDU encapsulates generally 10 messages). The node next to the GTW results the node with the worse power consumption due to reception and transmission of major number of messages. Considering the CC2510 values, WN equals 86 ms; if the activity cycle equals 1s, the obtained duty cycle is 8,6% in the worst case. As from the point of view of current consumption, the quantity corresponding to radio device in sleep results negligible and considering a 20mA transmission current consumption (-4 dBm) and switching consumption equal to reception consumption, in the worst case the average current consumption for this node is 1.86 mA. An analysis have been performed also on transmission technique, by modeling the network behavior, the result being a comparison between delivery success probabilities in function of packet loss probability when using classic or double transmission per packet.

Results show how the double transmission technique, presented in the access scheme object of this paper, leads to a constant success probability even in the case

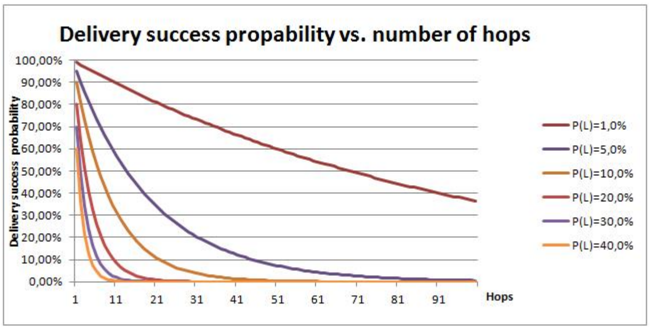

Figure 2.2. Delivery success probability - classic

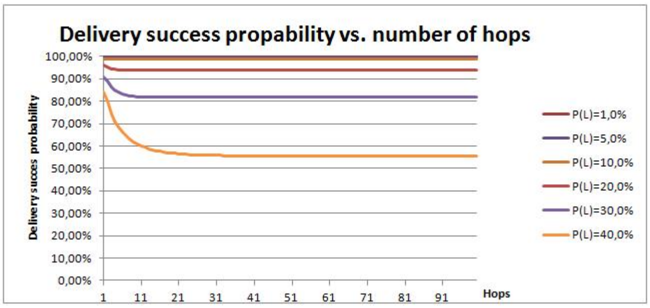

Figure 2.3. Delivery success probability - double

of a high loss probability due to the message re-transmission. The strength of the system object of this study represents the trade-off between performance given by innovative aspects and practical aspects as the final objective of the research was producing a commercial device.

2.2.4 RED-WINE Prototype

Due to the above mentioned constraint a prototype was realized (RED-WINE system, distributed solution) in order to test network behaviour in realistic testbeds; a first version of the above described protocol was implemented.

The WEDG GRAPE is a low-power, low-cost integrated multi-function device with following features:

- Crash detection (note: when installed on roadside steel barriers)
- Traffic monitoring(traffic occupancy, triggering of traffic anomalies like queue and congestion
- Environmental monitoring (temperature, humidity, luminous intensity, triggering of ice risk warning)

- Signalling (luminous path, blinking)

It is composed by two physical modules: the Head and the Box (connected through a pipe) that host the five logical modules: Acquisition Module (MA), Elaboration Module (ME), Signalling Module (MS), Communication Module (MC) and Power Module (MP). The GRAPE is characterised by small dimensions (i.e. 10X10X10 cm for nodes Head) and it can be placed along roadside on any available support (i.e. steel barrier, jersey rail, tunnel wall) and it requires extremely reduced installation time due to the fact that neither network nor power supply infrastructure is required.

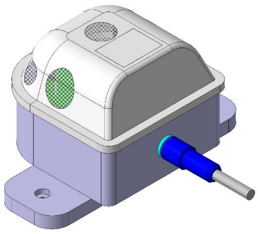

Figure 2.4. The Head of the GRAPE

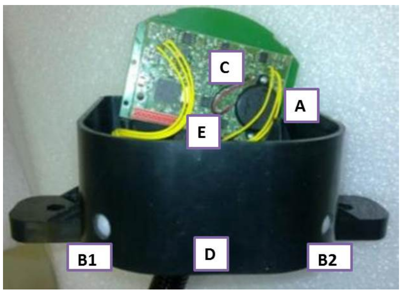

Figure 2.5. The sensors contained by the MA

The MA, located in the Head of the node, is equipped with different types of sensors: Accelerometer (A), Infrared (B1, B2), Temperature (C), Humidity (D) and Luminous Intensity (E). Sensors for other data points of interest (e.g. CO detector) can be easily integrated in the module. The MA also includes a metallic support to keep electronic Printed Circuit Board (PCB) for the MS that foresees two available positions on both side of the PCB, independent of the installation roadside and signalling direction. The technology employed for the signalling function is Light Emitting Diode (LED) in different colours, provided with dedicated lens. The device supports installations up to 6 LEDs (three on each side). For WEDG, MC is hosted within the Head of the node and it is represented by a dedicated radio module using the Texas Instruments CC2510 radio board. The device operates in 2.4 to 2.4835 GHz, unlicensed frequency range (¡ 10 mW). It has a built-in antenna, a versatile I/O for customization and a high performance and low power processor. The outdoor line-of-sight between nodes its up to 100m.

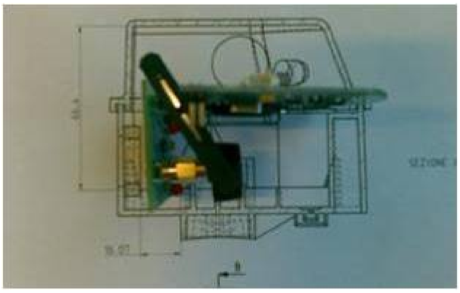

Figure 2.6. The position of MC within the Head

2.3 Indoor localization

2.3.1 Motivation

The correct determination of strategies and subsequent implementation of real-time communication and visualization systems can save a considerable amount of precious time during a rescue operation in confined spaces, like special transport infrastructures (e.g. bridges, tunnels, underground stations). When a crisis management intervention is needed, the potential to inappropriately manage, or unintentionally create an even worse situation, through human error and/or inadequate awareness of the whole situation, is particularly high. Confident co-ordination of actions, combined with efficient communication within, between and across teams, coupled with a high level of decision making under extreme levels of stress, are needed to deliver an effective emergency management response by large scale and complex organizations. To achieve this, both operations and training must address technical and non-technical aspects. [13]

Among all characteristics, one of the key factors shaping the successful implementation of evacuation systems is determined be the ability of such system to provide up-to-date location information in case of emergency. This will, for example, enable rescuers to do their job more efficiently, while reducing the risk to their own lives. The services they require include, for example, safe guidance through hostile environments, updated evacuation plans, information of how to reach trapped people etc. Detailed and timely knowledge of the exact position of the rescuers, while operating on the field, will be a major benefit to the rescue operation as will be information about the whereabouts of travellers.

2.3.2 Related work

Many indoor localisation and positioning techniques have been proposed in the literature in recent years'. Some of the proposed mechanisms, for example the ones that use infrared cameras or ultrasonic or laser transducers, although providing high accuracy, are very costly and suffer from several drawbacks, which make them less well suited to handle the adverse and harsh environment that will often result after an emergency situation (e.g. the presence of smoke and debris etc.) Consequently, localization techniques which utilize RF measurements appear to be more promising candidates. The literature reports numerous examples of localization methods based on signal strength of various RF frequencies. [14] [15] [16] As such, 2.4GHz was ultimately selected in this study as it is a widely used, low-power wireless technology designed for wireless mesh networks. Although an proprietary protocol was used in implementing the indoor localization system, it is acknowledged that it is necessary giving members of the rescue team additional hardware solely for the purpose of location and tracking.

There are two main approaches in the localization problem that utilize radio features: those that estimate the distance between two wireless nodes and those that estimate the angle of radio reception. AOA techniques require complicated equipment (special antennas, antenna arrays, multiple receivers on one node), leading to remarkably high costs and complex deployment. For distance calculations, extremely high node synchronization demands make time difference techniques e.g. TOA or TDOA unattractive, since the wireless nodes have limited processing capabilities. This therefore leaves the RSSI as the prime candidate for such range measurements.

RSSI measures the power of the signal at the receiver node and based on the known transmit power, the effective propagation loss can be calculated. Next by using theoretical and empirical models we can translate this loss into a distance estimate. Given a known transmission power and a good model of the existent wireless channel in the application area, the distance between a transmitter and a receiver can be estimated based on the received power. This method has been used mainly for RF signals and in wireless sensor network localization applications. RSSI is a relatively cheap solution without any extra devices, as all participating wireless nodes already have radios. The RSSI value, indicating the signal strength, is available at the physical layer, as part of the provided features of most modern wireless transceivers.

2.3.3 Application overview

The potential use of WSNs in emergency management has been present in the literature since 2000. Nevertheless, a survey [17] analysed over 20 WSN-based systems addressing various aspects of disaster management (pre/post disaster, monitoring/event detection, situational awareness, localization, simulations, experiments) and concluded that such technology is still not widely considered at the emergency preparedness documentation of governmental or telecommunication organizations around the world. This is mainly due to the drawback represented by the economic feasibility while respecting the technical requirements related to functionality and reliability. Further work related to the same topic highlights the fact that WSNs for disaster monitoring are still emerging technologies and much of the literature available is still theoretical: practical deployment guides using actual experience from field trials are few, if any [18] .

In case of the WSN presented in this chapter, the protocol design permits the automatic addition of new devices to the network through the entry of appropriate node address values in the gateway configuration files. A new node is automatically detected by the network, but being absent from a previous configuration, is considered as a mobile node and is heard by the network, but is not formally part of it. Exploiting this network property, it is possible to detect the position of a mobile node (its position on the axis of installation of the WSN) starting from the computation of RSSI values, which are collected by nodes of the network in communication range of the mobile node, called anchor nodes.

In the tunnel the anchor nodes are located along a preferred direction, along the road. In particular the sensors will be located on one side of the tunnel. This configuration imposes some limit to the possible resolution of the position of the sensor, since there is an axis of symmetry. In theory there are two possible solutions, even if one is typically out of the main carriageway.

For the specific case of the tunnel the problem is simplified by considering only the projection of the sensor to the geometry where the anchor nodes lay, in this case a line.

The rescue localization solution for the Tunnel shares the basic structure of the WSN solution for road infrastructure monitoring presented in the previous section, but adds a module that shall be worn by the person to be tracked, in this case the rescuer. The WSN Based Localization System is therefore composed then by:

- WSN Node
- WSN Floating Node (Rescuer Node)
- WSN Gateway
- WSN Server

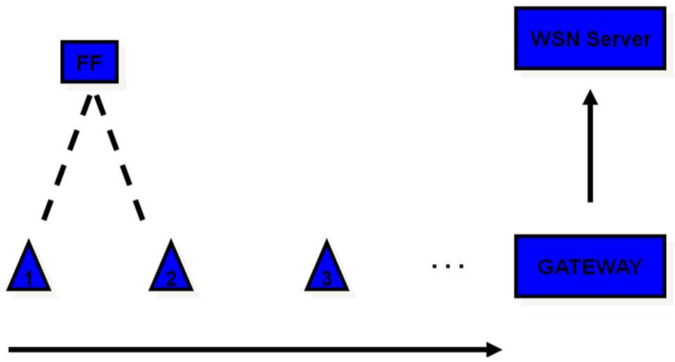

Figure 2.7. The simplified localization problem

The software infrastructure is being defined as follows: the WSN sensor node is composed of a communication firmware and a sensor firmware; in the rescue node there is only the communication module, since the sensing part is not necessary. Only the communication facility is involved in the localization process.

The Gateway node collects information from the nodes of the network and sends this to the WSN Server. In the WSN Server, the information is used to compute the location of the rescue person.

2.3.4 Context: SAVE-ME project, tunnel demonstration

SAVE ME project focused on the development of a system to both detect incidents in public transport terminals and other critical infrastructures (e.g. tunnels and other confined facilities) and support the timely provision of optimal evacuation guidance. Using application areas including metro (subway) terminals and road tunnels, SAVE ME focused on leveraging WSN capabilities to provide critical data that could then be used to provide optimal mass evacuation guidance to the general public and, giving special emphasis to vulnerable travellers, personalised guidance where required [19] .

A robust evaluation of the SAVE ME system was conducted under realistic conditions within two real-world facilities: the Colle Capretto road tunnel in San Gemini (Perugia, Italy) and the Monument metro station (Newcastle upon Tyne, United Kingdom).

While early pilot developments related to trial use-cases for SAVE ME were defined in collaboration with tunnel rescue operators at the Gotthard Strassentunnel, the final trial site selected was the Colle Capretto tunnel in Italy.

Colle Capretto is 1,171m in length and is located near San Gemini in Italy, forming part of the SS3bis national road (which is part of the E45 TEN route). It is a dual-bore construction tunnel, with traffic running in a single direction through each bore. The tunnel is monitored from a control room located in Perugia (about 70km to the north), not at the tunnel site itself. The SAVEME trial involved only one of the tunnel tubes; arranged to provide a two-way, single-bore environment as originally planned in conjunction with the Gotthard tunnel.

The SAVE ME trial took place on 31st May, 2012. With both tunnel bores closed for safety reasons, a multiple vehicle accident with dense smoke was simulated towards the centre of the tunnel. The trial itself involved 2 experimental runs with 40 volunteer travellers (including elderly adults and children), 15 fire-fighters, 5 ambulance personnel and 5 infrastructure operators.

2.3.5 Field test set-up

The installation for Colle Capretto (in the North-South direction tube), involved the deployment of sensing, localization and communication devices positioned in a 300m long area encompassing the sole safety by-pass within the tunnel. This location starts from 590m inside the north entrance and ends 890m from the north entrance (290m from the south entrance). Outside of the tunnel, a mobile command post vehicle was deployed as the bronze command location for all external-to-facility components. A wired Ethernet network was used to interconnect all machines at the command post location, linked to the gateways to in-facility systems through a wireless point-to-point 5.4 GHz link inside the tunnel. The WSN package for the tunnel trial comprised the installation of 10 WSN nodes and 1 mobile node for the network footprint, linked to a single gateway. This package was sufficient to envelop the trial zone within the tunnel with environmental, localisation and signalling services.

2.3.6 Personal contributions

The personal contributions of the candidate, developed within this PhD experience, are related to following activities:

- SAVE ME WSN package design
- Contribution to SAVEME communication schema definition and implementation of the schema on WSN Server side
- Contribution to indoor localization (road tunnel) of mobile node algorithms and implementation
- Development activities for WSN integration into SAVE ME system
- Validation plan
- Executive design of SAVE ME field trial and installation coordination

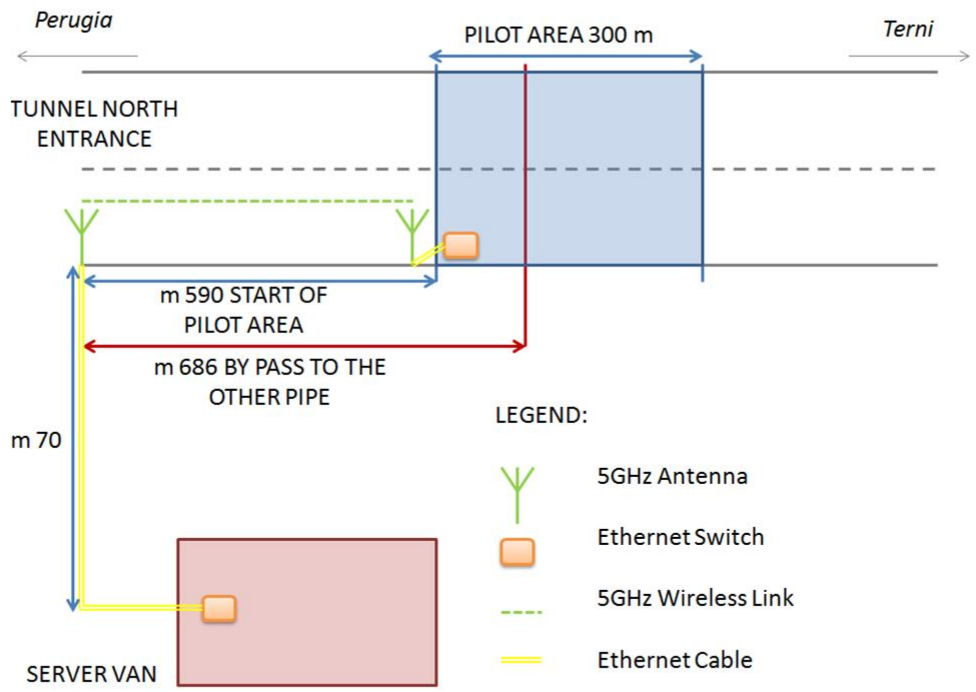

Figure 2.8. Colle Capretto Pilot Installation

2.3.7 Demonstration and application performances

During the SAVE ME project, 9 laboratory tests have been conducted. They were meant to test and evaluate the single modules of the system, in order to provide a solid basis for the final on-site tests. This section starts with presenting the pre-pilot evaluation of the WSN-based system for road side applications.

In order to evaluate network performances, a test sensor network with five nodes was active for 30 days, with a packet send period of 0.5 s. The resulting packet loss rate was between 4 and 10% (for an indoor scenario).

Localization tests were also conducted in an indoor environment, by deploying ten nodes, each 10m from the next, and performing RSSI measurements for neighbouring nodes every metre. Results show how the interpretation of RSSI slopes can provide localization information with an accuracy equal to half of the distance between the nodes. The figure below shows RSSI values for two nodes in a 30-measurement experiment: the measured accuracy is 5m.

The performance of the WSN described SAVE ME application and system can be defined as the level at which it operates under emergency conditions. [20]

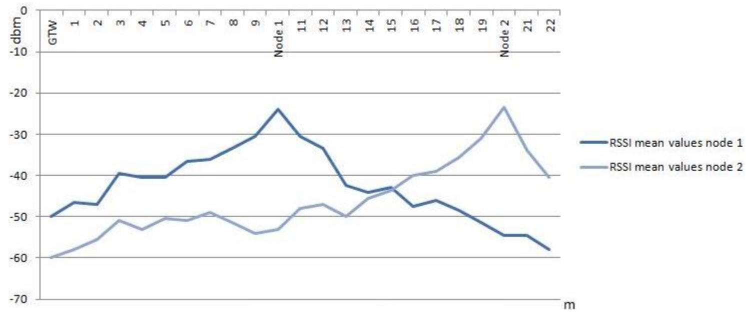

Figure 2.9. Indoor Localization Lab Measurements

Latency is a significant metric for the SAVE ME system as for any system involved with the safety and security of humans, the time taken to identify the event and implement the appropriate mitigation strategies is essential. The performance of the WSN network for road-side applications was evaluated by measuring the verified latency using the DSS logs to cross-reference the creation timestamp of messages sent by the WSN to the DSS with the logged reception time. The number of messages with a reception delay longer than 60 seconds were counted and used to assess the system latency. The number of messages with a latency value greater than 60 seconds was 8/229 (3.5%).

For the rescuer localization in the tunnel the mobile node was detected within a pre-specified threshold of 15m during the whole demo duration (100% of cases), by monitoring the actual position of the rescuer.

2.3.8 Conclusions and future work

From a technical perspective, the added value of the overall SAVE ME initiative was (i) development of a protocol and a data structure that contextualised a site by graph models, (ii) proof that the architectural principles of separation of concerns is exceptionally relevant in the context of complex, multi-component systems for real-world deployment, and (iii) provision of a mechanism through which real-time data could be exchanged in order to provide additional useful services for all involved actors.

The technologies and general concept presented in this paper have been recognised by the rescue teams involved in the SAVE ME project trials as highly valuable for assisting preparedness and reaction to emergency situations. Therefore, the WSN solution tested within SAVE ME may (i) improve the work of rescuers, (ii) reduce the overall evacuation time, and (iii) ultimately increase the level of safety of transport infrastructures.

The WSN technologies can be further exploited for monitoring the environmental conditions along the road/tunnel if coupled to a larger number of sensors on-board, for an early identification and localization of abnormal conditions, resulting in the adoption of appropriate preventative measures and ultimately the reduction of response times. The advanced level of industrialization of the WSN components may lead to a quick adoption by safety authorities.

Nevertheless, further research is needed for the identification of proper standards and performance levels needed for the definition of operational procedures. Further testing is needed in order to establish the limits of the WSN in terms of their scalability. This needs to be accompanied by regular technological updates and meetings between authorities and industries aimed at identifying ways of systematically integrating WSNs into current safety systems.

2.4 Intelligent street-lighting

2.4.1 Motivation

Street lighting in urban areas consumes today a very high amount of energy. Nowadays, in most of the cities, the streeligts system is driven by a fixed plan programming: they are simply switched off and on according to inputs of day and night sensors. Energy efficiency of lighting installations for smart cities can be significantly increased as requested by European Commission (EC) directives by deploying LED based lights. In addition, sometimes level of luminosity is reduced on a time based manner during the on-time.

Moreover, smart street lighting represents one obvious starting point in the deployment of smart cities. Aging street lights can eat up to 40% of a citys overall energy budget. There is a clear business case where implementing networked LEDs can drop this overall number by two-thirds, with the additional benefit of lowering operational costs, extending lighting network life spans, creating a safer environment for citizens, and establishing a canopy network under which other future services can be delivered. Furthermore, nowadays, LED technology is being implemented together with traffic management tecnologies, in order to maximize the efficiency of resources. [21]

This seemingly small task of upgrading street lights can have a big impact on a community.

2.4.2 Related work

A next step after introducing LED luminaires, has been the integration of intelligent functionality in todays streetlights. One of the first ideas was to add a communication module to each streetlight making it possible to control and monitor each luminary individually from a central station via wireless or wired communication. The following step is related to the approach of a combined lighting and traffic management system to realize traffic adapted intelligent management of streetlights by exploiting the dimming capabilities of LED streetlights. [22]

2.4.3 Application overview

The application where the WSN system described in this chaptere is implied is the management of public lightning system in base of traffic conditions in urban/parking areas.

The WSN system needs to be installed in order to monitor the traffic in the cross road in the green circle and to manage the public lightning system in that area. The application requires the integration of several wireless sensors in the system, in order to obtain a clear view of the traffic conditions, rapid detection of vehicle passage and consequently quick responses of the lighting system.

The sensors' system architecture is based on the deployment of wireless sensor nodes in the area of interest, forming the WSN in the observation field. Sensors and their MA are connected with radio interfaces to the deployed wireless nodes; parameters detected will be conveyed via the established wireless network to the WSN central sink (the gateway, GTW) for further processing. The gateway provides elaborated data to the TCC regarding network parameters and traffic data. This RED-WINE system and its design have been adapted to the requirements of the project.

The various modules that compose RED-WINE system are described:

- WSN nodes
- WSN gateway: The WSN gateway is an industrial PC provided with a radio gateway. The main functions of the gateway is to aggregate information coming from the nodes and forward it to the WSN centre, and implement the watch-dog procedure for the whole network.
- WSN server: WSN server is hosted in the control centre room. Its role is to receive information from various gateways on field, store all data into database and forward it to the appropriate module according to the specific application for further elaboration and visualization.

In this particular configuration, the WSN gateway has some extra functions:

- Driving the lightning system: electrical connection to the lamps networks allows their driving. It is considered initial and default configuration a reduced intensity of light. When a vehicle passage is being detected, the gateway drives the appropriate pin at 220V that deactivates the dimming mode of the lamps, and the intensity of the light reaches 100%. A timeout period has been calculated starting from the last received passage, in function of a minimum speed. For all three directions switching times of the lamps are calculated in order to ensure safe timings between lights reaching the 100% of light intensity and the actual passage of the vehicle. After the timeout period, the lightning system returns into the dimming state.

- Communicate the passage information to the other gateways in the system: an internal communication protocol has been developed in order to permit the communication of information from one gateway to the others

All data is being sent by the gateways at the control centre and is being stored into the Database, this permitting the analysis of all data and real time monitoring.

2.4.4 Context: COSMO project, Salerno demonstration

The COSMO (Co-Operative system for Sustainable Mobility) project is part of the European Commissions Competitiveness and Innovation Framework Programme (CIP). [23] Its aim is to improve the deployment of mobility services or ITS applications , in order to better road transport safety and to reduce environment impact.

The project does not develop new systems but it contributes to make operational existing prototypes and pre-commercial devices in real-life road context, like RED-WINE system, the central topic this chapter. The main objective of COSMO is to demonstrate the effects of these systems on the environment in terms of energy efficiency and environmental impact. Systems developed in COSMO could be classified in different categories, one of these categories being the intelligent streetlight management.

The Italian Pilot Site, deployed in Fisciano, the campus of University of Salerno implements several applications in the same geographical area integrated in an single architecture able to support advanced telematics services for a mobility sustainable characterized by an higher energy efficiency.

A key element of this application is the traffic adapted street light system with low energy consumption able to provide variable levels of luminosity and of power consumption. When traffic flow is low or no cars runs along the monitored path, a lower level of luminosity is sufficient and the streetlights can be dimmed to save energy.

2.4.5 Field test set-up

There have been installed three WSN networks involving a total of 10 wireless nodes, in order to cover the marked from north, south and internal road. The design below presents the streetlight management system described in the previous paragraphs. There are present 2 lines of lights (5 lighting points each) in green and orange and three management WSN gateways in red and WSN nodes in blue.

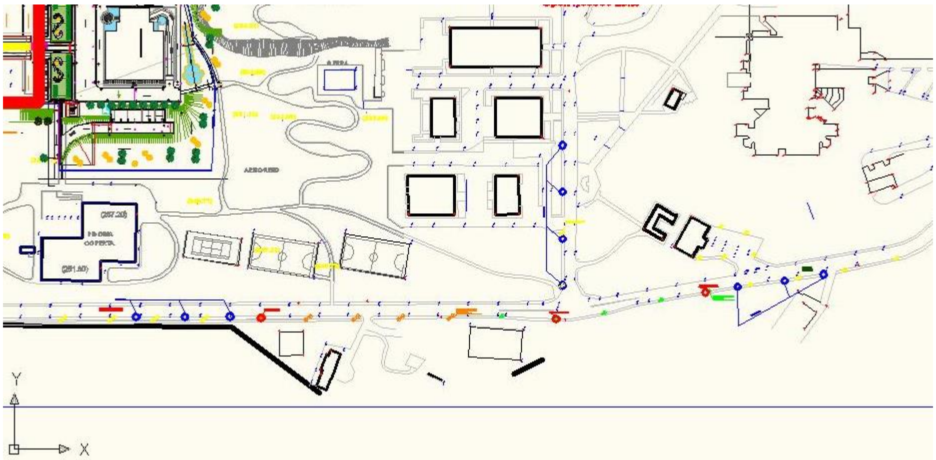

Figure 2.10. Executive design of field test

2.4.6 Personal contributions

The personal contributions of the candidate, developed within this PhD experience, are related to following activities:

- COSMO WSN package design
- Contribution to intelligent light dimming algorithm (urban areas)
- Validation plan
- Executive design of COSMO field demo and installation coordination

2.4.7 Demonstration and application performances

The intelligent streetlight management service relates to the use of street lights with two different levels of control (full power or energy saving) that reduce the electric energy consumption, since lights in full power operation are not needed at all night hours. The results are clearly positive; the initial expectative (hypothesis and target criteria) have been overcome, giving energy savings between 44% and 55%, depending on the level of control.

The system has been active for one month (May 2013) and the redundancy of the wireless nodes guaranteed the complete functioning of the system and data logging (information was stored regarding vehicle passages every minute). Furthermore, the carried statistical analysis show that the sample set is representative enough of the real population: the maximum distance from the observations data set mean value and the actual mean value are equal to 0,003481 kWh (standard deviation). [24]

The total energy consumption per day is reported for these three situations:

- Traditional Sodium vapour lamp (SON) based streetlights (Baseline)
- LED technology based streetlights
- LED technology with control based streetlights (Operational)

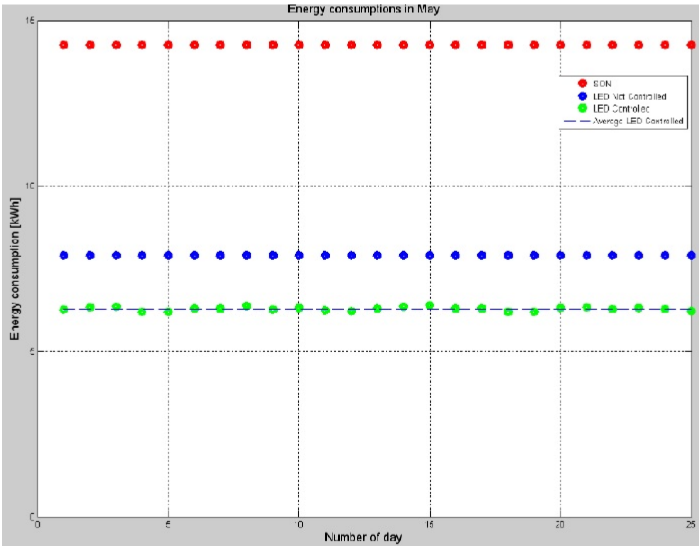

Figure 2.11. Application performances

As shown above there are high energy savings using the second and third system comparing with the traditional SON based streetlights. It should be noted that while in the first and second situation the energy consumption is always the same during the month (because the consumed power is always the same even if they assume different values), in the third situation energy consumption changes during the month of reference due to the different period of time in which streetlights are in full power and energy saving modes. In the same figure the average value of controlled LED situation is reported too.

2.4.8 Conclusions and future work

Given the application performances registered, deployment of this type of systems should be accelerated, starting with controlled areas like the ones represented by this pilot site, that can have less legal and exploitation constraints.

Nevertheless, further research is needed for the identification of proper standards and performance levels needed for the granularity of the system. Further testing is needed in order to establish the limits of the COSMO WSNs in terms of their scalability to larger urban areas.

2.5 Traffic monitoring in highway environments

New infrastructures cannot solve congestion and emissions problems due to high traffic intensity, but ITS, by applying telematics to transports, can provide new services, able to reduce congestion and pollution, without building new infrastructures or expanding existing ones.

Although the effectiveness of ITS strategies in improving many kind of transport systems had been widely analyzed and proved by the scientific community, most proposals never became real systems due to the lack of adequate traffic monitoring technologies: most ITS applications require traffic information in real-time and with high quality and high resolution.

Conventional technologies for traffic monitoring, used for many years, are the so-called intrusive methods, and consist of a data recorder and a sensor placed on or in the road. However, high maintenance and installation costs are limiting the usage of these fixed detectors to a few roads, all included in well known congestion zones, thus making even a city-wide approach unfeasible. At the same time, their high cost, raised the interest of the transport community on collecting traffic data from tracking cellular phone or GPS, which could be technologically feasible and a cost-effective alternative. Unfortunately, existing reports like [4] do not target these new trends to replace the existing sensors but rather to act as complement technologies, due to major drawbacks as accuracy and reliability.

Therefore, WSN are a promising candidate as a traffic monitoring systems, able to overcome to the main issues of conventional systems and at the same time able to keep its cost at a sustainable level. Their unique capability to combine information coming from low-cost and low-power sensing devices communicating through a scalable self-configuring wireless networking, allows to monitor long stretches of road with a high spatial resolution at a reasonable cost.

2.5.1 Related work

The main features of traffic monitoring based on a Wireless Sensor Network (WSN) and its benefits to ITS performance have been discussed in [6] . That paper clearly shows that most of existing monitoring systems are wired. This makes wired systems simpler to design and less expensive than wireless systems with energy-autonomous nodes, but only if the cost of the deployment of the cables and the installation of the nodes is not considered: whenever an existing high-traffic road must be equipped with a sensor network, the wireless, energy-autonomous solution is not only less expensive, but it also requires a much shorter time to be deployed. Another advantage of wireless solutions is the possibility to increase at any time the density of nodes, in order to cope with changing road characteristics. This adaptability is obviously very beneficial also form the economic point of view, allowing for a progressive deployment of nodes, in accordance with actual needs of the road operator. Finally, the maintenance is greatly simplified by the fact that any node can be replaced by a new node simply unlocking it from its cradle and locking in a new node.

These characteristics make WSN a promising technology especially for safety applications that are assuming an even increasing role in ITS. A general architecture of wireless monitoring network has been presented in the referenced papar underlying critical constraints and project characteristics that require deeper study. Major communication protocols and technologies have been listed and compared with focus on the requirements of interoperability, security, flexibility and adaptability.

In scenarios where high-density data detection is a fundamental requisite for safety/control applications, sensor failures or inconsistence of measured data could severely impair the reliability of the overall monitoring network. Therefore, the sensor network must also be self-healing, which can be really difficult for wired networks, where a cable failure can power down, or simply isolate, a big chunk of the network nodes. A WSN, under some conditions, like the one described in this chapter, can be self-healing.

Getting back to the application topic of this section, a study on existing AID methods measured performance level for three criterion (Detection Rate, False Alarm Rate and Time To Detection) and targeted as best algorithms those who imply the use of ARIMA techniques or based on traffic models (McMaster). None of these represents though the appropriate choice to be applied in our case, due to the fact that both techniques need as input more traffic variables, not available when using low cost sensing technologies, and due to implementation difficulties and costs. Therefore, there have been analyzed three methods available in recent literature, that have been considered adapted to this case study.

The first [27] is based on the analysis of the difference between cumulative occupancies from the generic detector couple between which anomaly could occur. The method aims the individuation of anomalies in situations where traffic is relevant and therefore might induce effects on vehicle delay. The reference scenario is the highway with homogeneous road stretches, monitored by sensors positioned at reduced distances, necessary if short time for anomaly identification is required.

The second method [28] , in order to point out bottlenecks that create flow saturation phenomena within road stretches, proposes a comparison between cumulative curves of vehicle count and speed. Since due to short distances between sensors the cumulative curves might not clearly highlight interest phenomena, the author describes a method based on oblique diagrams in order to manage the comparison process in a more efficient way. The method can also be applied in non-homogeneous stretches of road, for example, those that present a variable lane number along the monitored area.

The third method [29] , based on the hypothesis of disposing a diffused monitoring system along the road, proposes the individuation of traffic anomalies on the base of comparisons between traffic states that refer to sensor couples. This approach foresees predisposing space-time diagrams that map possible traffic states when an anomaly is present in order to individuate, through state comparison for sensors couples, the trigger of the unusual phenomena. The method, illustrated for a case of homogeneous stretch of road, can also be extended to cases relative to non-homogeneous stretches of road.

The present work makes use of the easiest achievable measure using the available sensing technology: the occupancy, which makes the first of analyzed methods the most appropriate to be used. The second method could be used in a second phase of scenario analysis if reliable data of vehicle count and speed for non-homogeneous stretches of road could be provided through the use of our collection tool. The application of the third method was retained too complex as it integrates a state mapping on a time-space diagram, that needs to be calibrated for the monitored road stretch.

2.5.2 Application overview

The application requires the integration of several wireless sensors in the system, in order to obtain a clear view of the traffic conditions, rapid detection of vehicle passage and consequently quick elaboration of the data and signalling of eventual traffic events through a dense monitoring of the desired stretch of road.

The RED-WINE system architecture is based on the deployment of wireless sensor nodes in the area of interest, forming a wireless sensor network in the observation field. Sensors and their acquisition module are connected with the radio interfaces to the deployed wireless nodes, as described in the introductive part of this chapter; parameters detected (the occupancies, through the infrared pyro-electric sensor) will be conveyed via the established wireless network to the WSN central sink (the gateway, GTW) for further processing.

The gateway provides elaborated data to the Control Centre regarding network parameters and traffic data.

This system and its design have been started from the basic RED-WINE prototype and then adapted to the specific requirements of the application.

The system design is described in this section. The various modules that compose RED-WINE system in this case are:

- WSN nodes
- WSN gateway (RSU): The main functions of the gateway is to aggregate information coming from the nodes and forward it to the WSN centre, and implement the watch-dog procedure for the whole network.
- WSN server: WSN server is hosted in the control centre room. Its role is to receive information from various gateways on field, store all data into database and forward it to the appropriate module according to the specific application for further elaboration and visualization.

An innovative traffic algorithm for AID was created in order to elaborate traffic information and detect queues situations.

The algorithm is based on two fundamental factors:

- Vehicle count
- Occupancy (for every sample equals 1 if pyrometers detect motion and 0 otherwise)

and derived parameters:

- Occupany sum for 3, 10, 30 and 60 seconds intervals
- Exponential filters (=0.2) of above sums: exp3s, exp10s, exp30s, exp60s

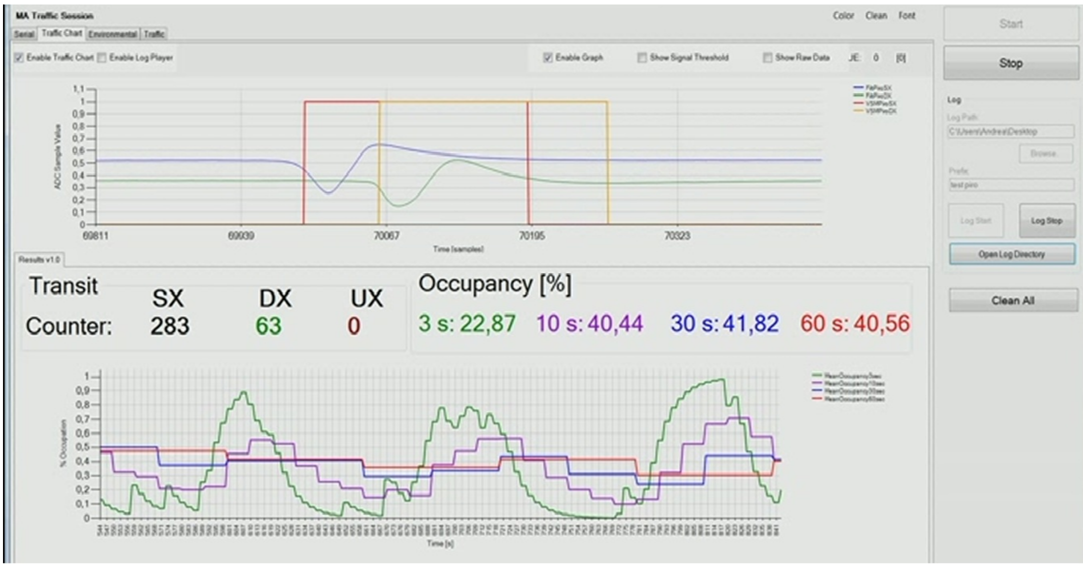

Figure 2.12. Signal real time elaboration

These values are sent by the nodes every three seconds, and forwarded by the gateway every 12 seconds: in this way a real time traffic monitoring is guaranteed. When the values reach the centre, they are filtered in order to recompose the signals. The traffic algorithm has as an input these signals, its implemented within the WSN server and its composed from two distinct FSM:

- Fast Traffic Status Machine (FTSM)
- Slow Traffic Status Machine (STSM)

The FTSM is based on exp3s signal and its output is given by 3 indications that characterize the input signal:

- Intermedium (value minor than 0.75)
- High (value higher than 0.75, observing window 60s)
- Break down (value minor than 0.1, observing window 90s)

The STSM has as an output 5 LOS (represented int the figure below), that characterize the traffic flow, and it is based on:

- FTSM state every 60 seconds
- ALARM = duration of exp3s signal in break down state
- Exp60s signal
- Vehicle count in the last 60 seconds
- Medium value of 5 vehicle count calculated on a 60 seconds window

2.5.3 Context: COSMO project, Vienna demonstration

The COSMO (Co-Operative system for Sustainable Mobility) project is part of the European Commissions Competitiveness and Innovation Framework Programme (CIP). [23] Its aim is to improve the deployment of mobility services or ITS applications , in order to better road transport safety and to reduce environment impact.

The project does not develop new systems but it contributes to make operational existing prototypes and pre-commercial devices in real-life road context, like REDWINE system, the central topic this chapter. The main objective of COSMO is to demonstrate the effects of these systems on the environment in terms of energy efficiency and environmental impact. Systems developed in COSMO could be classified

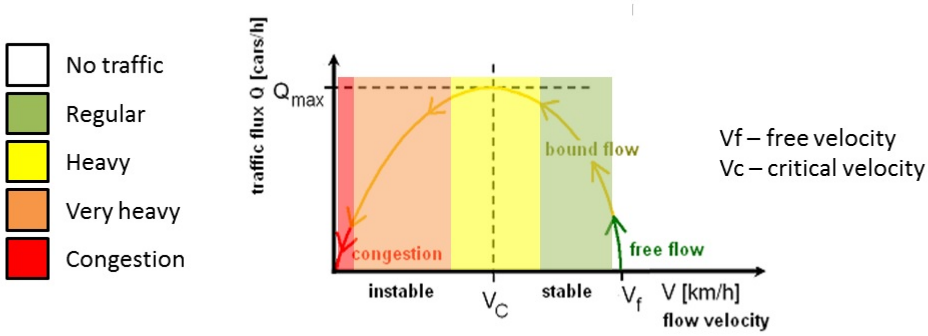

Figure 2.13. Output of the traffic algorithm

in different categories, one of these categories being the real-time traffic monitoring in a high-way environment.

The Austrian test site was located in the south of Vienna. In detail, the construction site being the Austrian pilot site is situated on the motorway 2 (A2) between Kottingbrunn and Baden. Motorway 2 is the main route for all people coming from the south and south-east to their work place in Vienna.

The objective of the Austrian test site is to demonstrate measures to raise energy efficiency with traffic management systems for temporary installations in an interurban test site. In order to reach this aim, the most important element in this installation is the traffic monitoring system, in order to be able to provide an advanced infomobility service to both operators and drivers in contact with the road-works area.

2.5.4 Field test set-up

The RED-WINE WSN was involved in middle and long-term installations (1-3 months) deployed in Vienna test-site, on A2 motorway (Austria) in 2011 and 2012 during mobile road-works. A three-node and a six-node network collected traffic data for more than one month in every installation phase. An example of the networks installations is shown in the figure below:

The on-site installation was preceeded by various preliminary field-tests performed at Maroncelli roundabout (Turin, Italy), where the following configuration was deployed:

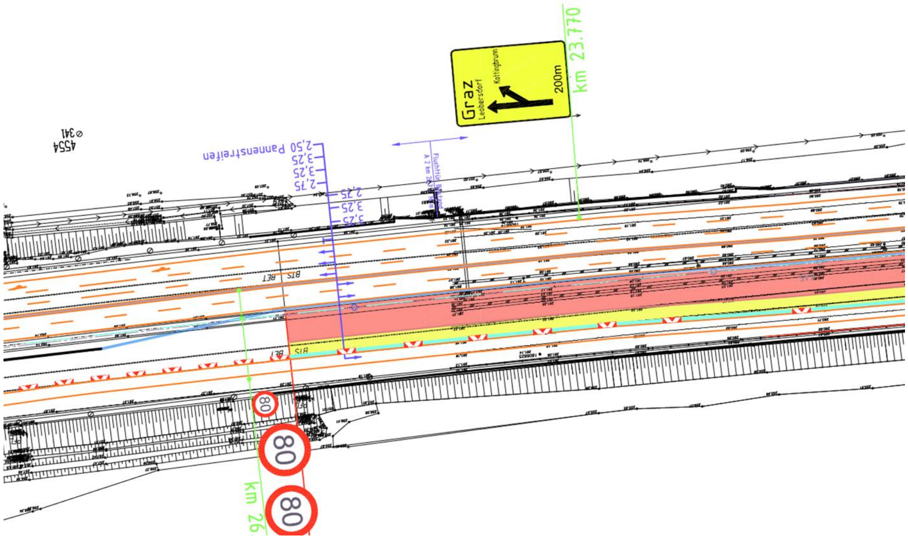

Figure 2.14. System positioning example

Figure 2.15. Maroncelli roundabout configuration

2.5.5 Personal contributions

The personal contributions of the candidate, developed within this PhD experience, are related to following activities:

- COSMO WSN package design
- Contribution to traffic LOS detection algorithm (extra-urban areas)
- Validation plan

- Executive design of COSMO field demo and installation coordination

2.5.6 Demonstration and application performances

The performances of the AID detection algorithm were tested in the Maroncelli roundabout test installations and results were compared to video registrations.

Figure 2.16. Maroncelli roundabout: still vehicles

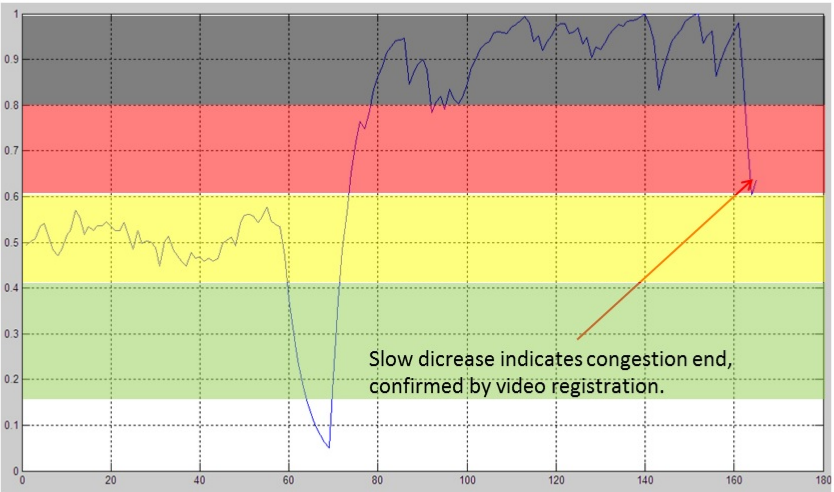

Figure 2.17. Maroncelli roundabout: congestion

During the COSMO installation periods, due to redundancy and robustness of the system, 98% of data reached the TCC and traffic estimation derived from the system was compliant to legacy system data (reference data from ASFINAG - the

Austrian Motorway owner - indicates circa 1800 vehicles/h per lane due to peak times, confirmed by the WSN based monitoring system).

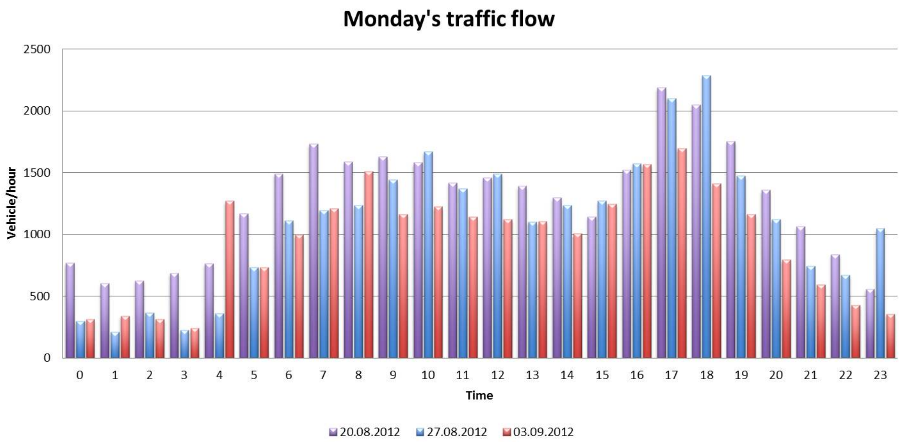

Figure 2.18. Vienna installations: Peak traffic flows (Monday)

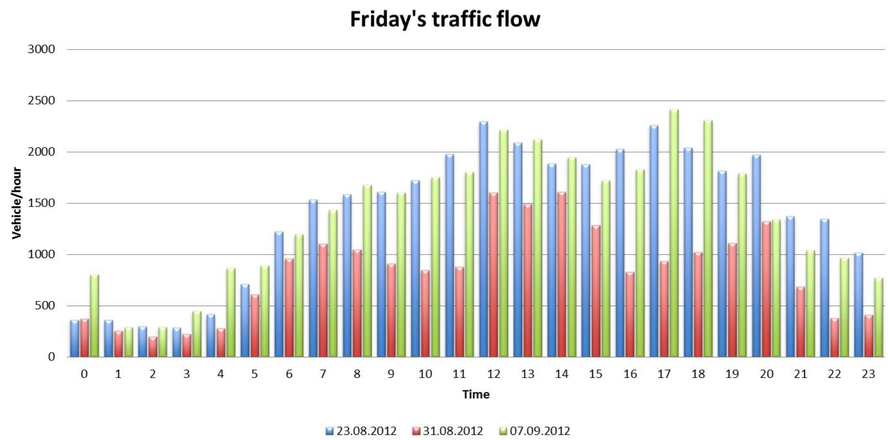

Figure 2.19. Vienna installations: Peak traffic flows (Friday)

2.5.7 Conclusions and future work

The experiences acquired during various phases of this work showed that the WSN object of this research opens innovative scenarios: the possibility of having a large number of acquisition devices that placed at short distances between them, that allow the precise collocation of an event in time and space. In the same time, using energetically efficient elaboration and transmission techniques makes sensors independent in terms of power-supply. Future work considers the improvement of the AID algorithm, of the synchronization method and a band allocation algorithm will be proposed in order to ensure all network the same transmission rights and prevent an excessive band quantity corning from upstream nodes.

Chapter 3

I2V Communication for the provision of Traffic Light Assistant service

3.1 Introduction

European travelers will soon benefit from improved safety, energy saving, efficiency, comfort, real choice between travel alternatives and personalized response during their journeys thanks to the exploitation of cooperative systems. In C-ITS, revolutionary concepts, as V2V and V2I communication, are on their way to become concrete: European vehicles will be fitted with communication capabilities starting from 2015, even though the development of cooperative systems, which involve the real-time exchange of data between vehicles and the infrastructure, is in many ways a logical extension of the move towards integration of individual telematics systems which began several decades ago.

Such systems are expected to bring significant advantages in both the urban and interurban road environment. These include improvements in safety as well as traffic flow efficiency and information for road users. Applications in the safety area aim to increase drivers awareness by providing, for example, advance warning of dangers ahead, imminent changes in traffic signals, and speed recommendations based on the current local road status. The cooperative approach makes it possible to collect more accurate and detailed data on road conditions and traffic status than at present, and therefore to offer drivers information with greatly improved content, timeliness and accuracy. They also open the way to safety-critical applications where vehicles are always connected. [30]

The wireless technologies used for the continuous communication among different vehicles and between vehicles and the road infrastructure are the cornerstone of co-operative systems. These technologies concern the networking & transport and access layers of the reference protocol stack of an ITS station and can be divided into two main categories: general and vehicular specific communication technologies. This category comprises well known wireless communication technologies such as cellular networks, WiMAX, WiFi, infrared, bluetooth, DVB/DAB etc. which are not specifically developed for vehicular networks but play a significant role for future deployment of cooperative systems. [51]

In order to achieve the presented purposes, a number of cooperative services can be integrated into central systems using latest message standards (e.g. CAM, SPAT, MAP, DENM), different communication technologies (e.g. UMTS/LTE, ITS G5) and use cases from the different standardization bodies (e.g. CEN, ISO, ETSI) or the C2C Communication Consortium [32] , among others. The main related service deployed in urban environments is Traffic Light Assistant, that provides in-vehicle information about signal phase and timing of traffic lights and intersections topologies.

The most significant barrier when facing real implementation of C-ITS solutions like the one described above is related to the uncertainty of its effects in specific situations, and therefore there is the need to provide the stake-holders the evidence regarding their benefits. To this purpose simulation activities need to become more and more part of the design process.

There are yet no standard approaches to C-ITS services simulation. Therefore, this chapter presents a solution for the simulation of co-operative services and an example to its application for the impact assessment of TLA.

The remainder of this chapter is structured as follows: a first section is giving an overview of the main C-ITS services for which the deployment phase has already started. Then, a following section is deeply describing TLA service from both historico-economical and technical point of view. Finally, the third section describes an innovative approach for the simulation of C-ITS services, and the application of this approach for a TLA specific situation. A discussion on application performances and some final considerations on conclusions and future work close the chapter.

3.2 Co-operative ITS services

Cooperative ITS systems (also known as C-ITS) are a rapidly growing sector in the field of smart transport. C-ITS allow vehicles to communicate with each other and with the infrastructure, in order to increase their awareness about the road environment, through the means of innovative services related to specific situations: dangers on the road, unexpected manoeuvres, traffic lights status. The main related services can be deployed either in urban or inter-urban environments and are the following, as described in [33] :

- Traffic Light Assistant (Urban): This service provides information about signal phase and timing of traffic lights and intersections topologies thought the use of the standardized SPAT (SAE J2735) and MAP (SAE J2735) messages respectively. This messages are received by vehicles based on its position, which is communicated to the Traffic Management Centre using the CAM message (ETSI ITS). In consideration of the current position, speed and driving direction the vehicle "knows" about the traffic light phase at the next intersection and can thus inform the driver about the ideal speed to reach the intersection during the green phase or, when stopped because of a red light, show the remaining time to green.

- In-Vehicle Signage (Urban / Inter-urban): This service provides different types of information directly to the vehicle as traffic signalling such as road works, incidents, jams, speed limits, etc. Much of this information, nowadays, is shown to the driver though fixed signs and variable message signs along the road or streets. For practical reasons, there a limitation of the quantity information that can be shown to the driver and, therefore, this service can offer additional pertinent information to the driver which is not possible in other way. For instance, in the situation of a traffic jam, the traffic management centre could inform the driver about the length of the queue and, additionally, provide suggestions on how to avoid such condition. Messages involved in this service are the CAM message to inform the position of the car and the DENM (ETSI ITS) message that contains the information of the events and signs mentioned before.

- Public Transport Priority (Urban): Public transport priority at traffic signals is an important measure to increase the efficiency of urban traffic management to better handle ever-growing traffic volumes. Vehicles arriving to intersection will ask for priority by means of the SRM (SAE J2735) or CAM messages and, based on a number of factors (e.g. traffic conditions) priority will be granted or rejected. This latter communication to the vehicle is done though the SPAT message containing the prioritization response. In summary, the service makes public transport more attractive due to faster travel times and improved service regularity. Moreover, passenger satisfaction is higher and complemented by additional benefits including improved energy-efficiency and, in consequence, reduced pollution.

- Traffic optimization (Urban / Inter-urban): This service leverage on the large quantity of vehicles, or new sensors, that are constantly driving along urban and inter-urban areas of a city. By receiving the CAM message sent by vehicles able to generate such message, the system can, for instance, dynamically adjust the traffic light cycle of an intersection, in order to avoid congestion and minimize waiting times. Among other things, with the current traffic volume data gathered from the field, the system can improve the monitoring of individual and safety-relevant data on a large scale enabling an increased level of detail and reliability in traffic and safety monitoring and thus identifying possible interventions, it can also smooth traffic flow due to optimized control of vehicles and infrastructure, and lastly, it can improve the current deployed algorithms for cooperative traffic control optimization.

3.3 Traffic Light Assistant

3.3.1 Application overview

One of most interesting C-ITS application is the so-called Traffic Light Assistant (TLA). This service is able to provide useful indications for crossing of intersections with traffic lights in order to reduce the waiting time, energy consumption, emissions, and increase the comfort level of the drivers.

The driver is the direct beneficiary of this service, but it can also be seen as a complementary tool to the strategies of public transport priority, as it provides information to the driver about the optimal speed or time to devote to the bus stop, considering the state of the next set of traffic lights and eventual requests for traffic light priority.

The TLA application is based on SPAT/MAP messages and uses the communication of the signaling information from the traffic light controller (e.g. red, amber, green) to all individuals and vehicles using an intersection (e.g. vehicles, bicycles, pedestrians), in order to support the following use-cases:

- In-vehicle-information of SPAT for the preparation of the driver for increase of the awareness.
- Green light optimal speed advice for a more smooth and fluent traffic flow with less stops and less emission.
- Start-Stop suppression enables the vehicle control to avoid inefficient motor starts on stops at red lights with only a view seconds.

Cellular networks are evolving rapidly to support the increasing demands of mobile networking. Although these networks are designed for voice data exchange they can be applied also to vehicular networks especially for information and entertainment applications. Nowadays, cellular networks migrate from GPRS, to UMTS, to LTE standards, increasing bandwidth and reducing delay times making these networks appropriate also for other kind of applications such as efficiency services. Therefore, SWARCO is following this trend during the deployment process; consequently, the analysis presented in this chapter is related to TLA provided through the cellular network.

3.3.2 Challenges and alternatives

The information needed by TLA services is available in a small number of systems, such as UTOPIA [34] . Therefore, in recent scientific literature a some authors have tried to analyse issues related to traffic light phases and timing prediction, which becomes a challenge depending on the traffic light system controllers and configurations:

- Fixed time
- Plan selection (traffic actuated plans)
- Simple traffic actuation (pedestrian, bus priority)
- Adaptive traffic control (UTOPIA)
- Highly traffic actuated

Therefore, in order to create a usable and effective TLA service in all conditions described above one of the most important information to have is the state at any time of the traffic lights. Having an universal predictor able to give reliable forecast to the phase duration knowing only the states of the lights in the intersection and their historical data it would be for sure a valuable instrument to made TLA usable. In a simulation environment, this problem does not exist as no communications issues are expected, but in a real application, this become a challenge (especially in case of adaptive or higly actuated traffic light control). Indeed, modern traffic lights are often actuated by traffic states information gathered using detectors and used in real time, but it is not always possible to generalise the algorithm that links detector signal to traffic light state duration. Having a universal predictor able to give reliable forecast to the phase duration knowing only the states of the lights in the intersection and their historical data is for sure a valuable instrument to made TLA usable. In line with this statement, in [35] the authors use a Kalman filter to predict future probability distributions instead of future switching points. This method can give probability distributions for different kinds of actuated traffic lights, and can work also with high delay in data transmission, but is not able to return an exact value for the switching time. Authors have not noticed that traffic lights phase length usually stay around a mean, using a cycle of fixed time introduced later in this work. As a result, authors are considering like a variance factor something that in reality is just a deterministic answer of the traffic light to something caused by the detectors.

An approach similar to the one implemented in this paper can be found in [36] . Here, the Author used historical data to build transitions matrices on phase changes and phase durations, giving a prediction and a probability over that prediction. Then, Montecarlo methods have been used to choose between these predictions. In any of the cases observed and known, the Author highlighted that try to predict future data just using historical one, with no other hint on external factor as traffic or public transport is not an easy task, and any forecast is linked to a percentage of error. As said, the prediction algorithms that run within the TLA service presented in this paper are based in most cases on a statistical forecasting method. The basic structure for the forecast is the pattern of the conditional probabilities of the time to next signal group switching. The conditioning element is the intersection status, which is qualified by a list of significant data (such as type of signal plan, time-of-day, time from last switch, signal group active on last switch, time from the start of current cycle, current and previous detectors activations). In the next sections, main predictions algorithms are presented into detail, also providing an overview about the results of evaluation campaigns implemented in Berlin (800 controllers) and in Garmisch-Partenkirchen (25 controllers, with complex actuation strategies). In the operation phase, the choice among the most accurate algorithm is automatically executed by OMNIA [37] , by analysing in real-time the model with the most accurate prediction. This selection is based both on the historical profile of accuracy and on the last phase transitions prediction. This selection is not trivial nor invariant because, as shown in next sections, it may happen that in certain time windows during the days a traffic light controller changes its control strategy, or specific actuations (such as area-wide coordination strategies) occur.

In [38] , the authors deal with the challenges of an extensive prediction of complete urban areas' traffic light networks. The same algorithm presented in [35] is now implemented on a large-scale environment. Authors introduce a real-time prediction algorithm and back-end implementation that is able to generate signalling predictions based on SPAT for adaptive traffic lights of an entire urban area. The approach is able to meet the requirement of dealing with high latency times for historical data and incomplete data sets. The proposed algorithm is able to provide predictions for 85% of the adaptive traffic lights with available historical SPaT in 65% of the time and thereby reaches an accuracy of 92% to 97%.

A similar study is presented by AUDI [39] . In this paper we observe an implementation of GLOSA system tested in Ingolstadt. The system tries to predict the time to the next switch between phases using probabilities associated to any possible state the traffic lights can provide. This lead to the first problem that not always the traffic light architecture is known or can be easily find out especially for actuated traffic lights. To improve the predictions for highly dynamic traffic conditions the system also introduce day classes and time windows, this means that each reported signal change is categorized by the type of day (weekday, holiday) and by the time window it is in (e.g. 11:00 am till 12:00 pm). This requires a complete calendar including holidays, school vacation, or even sports events for the city in which the traffic light is located. Especially for rare day classes a longer learning phase is necessary to collect enough data for the forecast to function properly. One of the problem observed is that sometimes the transition probabilities are not highly significant. Authors tried to improve them by observing more steps backward, this in some cases helped to find information that is more reliable. In the end, Authors decided not to compute predictions for more than 30 seconds in the future - due to their uncertainty. An accuracy of 2 seconds was reached in the 80% of the times at 15 seconds to transition and for 95% at 6 seconds to transition, using fixed time measurements (close to the signal change the traffic light has less degrees of freedom due to red-amber or amber phases and blocking times). Authors used variance of the data as an estimator to determine the confidence of the information and to some extent implemented some of the techniques used by SWARCO, but analysing only SG duration (neglecting in this way other relevant time windows, such as meta-cycles). As well, duration of the prediction window is considerably lower (30 seconds against 90 seconds).

3.3.3 Behind TLA: generic architecture and message protocol

Services described above need an integrated platform capable of fusing all the information coming from different sources and apply business rules that provide the required output for traffic management. This section provides a functional architecture for the provision of C-ITS services, based on the OMNIA [37] model, which is able to collect and integrate a large variety of existing systems and infrastructure equipment into a single user interface. This platform would then apply cross-system business logic to provide the necessary cooperative functions required for these services.

The TLA application is based on SPAT/MAP messages [50] , belonging to the Facilities layer from the generic ETSI ITS architecture for the ITS station [49].

The Facilities layer handles application support, information support and session support functionalities. Application support refers to functionalities such as download and initialisation of new services, automatic discovery, and HMI capabilities. Information support handles data management, considering that data will be mostly geo-referenced and location specific. In addition, it is important to note that the

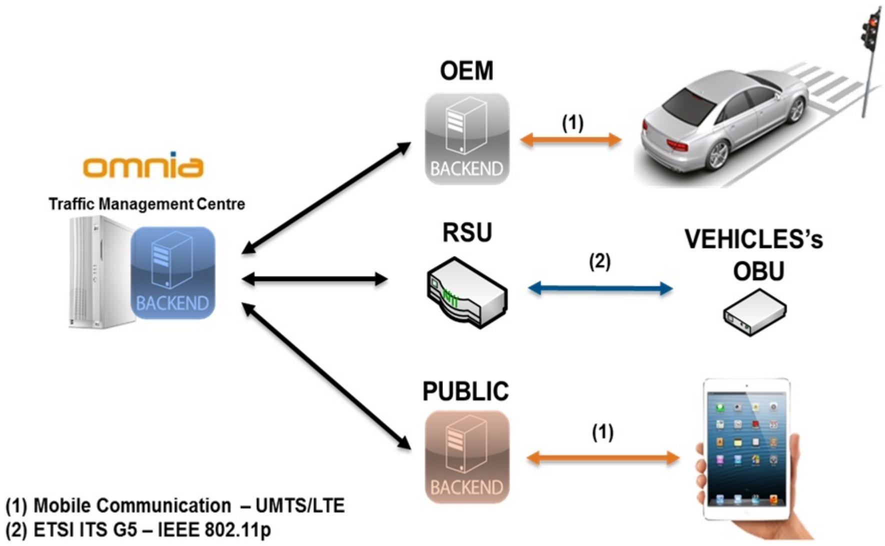

Figure 3.1. Generic architecture for the provision of C-ITS services

utility of the data exchanged will be time-dependent, which requires the data to be validated so that users trust its content. Session supports handles the creation and maintenance of a link between nodes, with different implementations depending on the application and its time-critical nature.

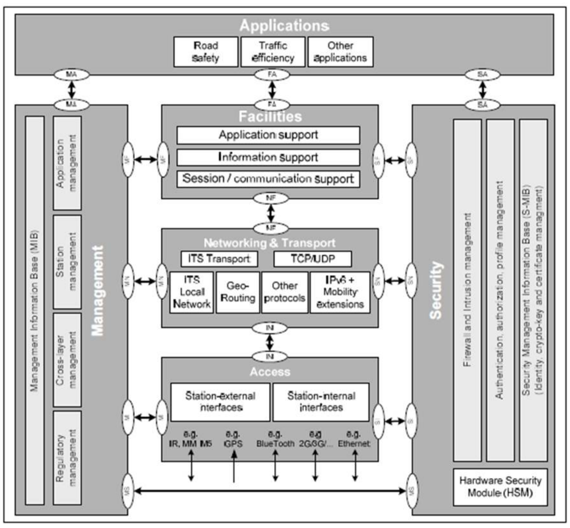

Figure 3.2. ETSI generic architecture for the ITS-Station

The MAP message defines the topology of an infrastructure area. It includes all the roads for vehicles, public transportation and the paths for pedestrian crossings. It includes the topology for an intersection and the topology for a road segment. In future enhancements the MAP message will also include additional topology-descriptions like roundabouts intersections.

The area of an intersection described in the MAP is suggested to cover about 200 m of the approaches, starting from the position of the stop line. If a neighbor intersection is closer than 400 meters, the MAP description may be done up to an extent of approximately the half distance between the intersections.

The SPAT message defines the status of the signals in an intersection. The status information includes general operational states of the traffic controller, the current signal state, the residual time of the state before changing in to the next state, the right of way for each allowed maneuver (connection between lanes) and assistance for crossing the conflict area of. Additionally SPAT may include detailed green way advisory information and the status for public transport prioritization.

The signal information from an intersection controls dynamically the "right of way status" of a connection between an ingress lane (driving direction toward conflict area of the intersection) and an egress lane (driving direction away from the conflict area of the intersection).

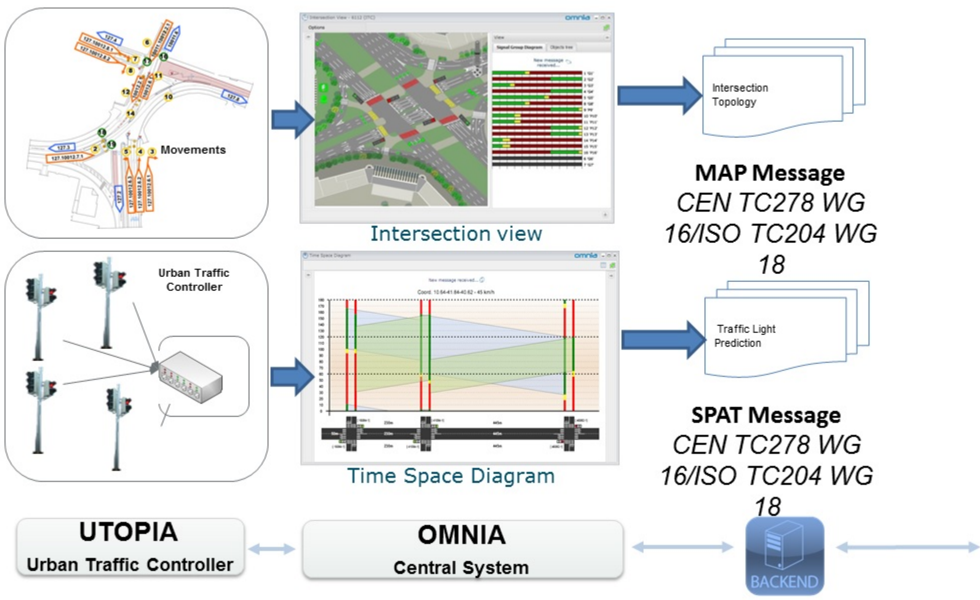

Figure 3.3. TLA message protocol

3.3.4 Impact assessment in literature

Even though only in a small number of systems the information needed by TLA services is available, in recent scientific literature a few authors have tried to analyse issues related to traffic light phases and timing prediction and to estimate the benefits of this service for drivers and public authorities.

One of the first works is [40] , where is proved that using an optimal driving strategy it could be possible to save an average of 30% of fuel consumption and also if just the first vehicle is equipped with this system the average speed of the platoon is increased.

In [41] a TLA is tested in a simulation environment. Results suggest that the TLA application has a positive effect on reduction in stop time and fuel consumption. The higher the TLA penetration rate is, the more benefits we have with a maximum of 80% reduction in stop time and up to 7% reduction in fuel consumption in a high traffic density scenario. There is a critical point of 50% of equipped vehicles where the effect of TLA starts to be more visible. As the density decreases, the benefits for fuel efficiency are reduced, but there is still improvement compared to non-equipped vehicles. The traffic efficiency on the other hand is increased with the decrease in traffic density reaching 89%. There is also an optimal activation distance, where the TLA application should advise the driver and this is near 300m from the traffic lights but it depends slightly on the road network. Closer to this distance, the time to react is limited and further away there are no more benefits. Further performance analysis can be found in [42] . For what specifically concerns carbon dioxide emissions, in [43] the authors state that both traffic lights actuation technology and on board GLOSA system penetration have a similar impact on CO2 emissions, adding that under high traffic conditions GLOSA system is less effective and sometimes could also cause an increase in the emissions. In the end, they concluded that Green Light Optimal Speed Advisory (GLOSA) systems are envisioned to be not only environmental friendly by reducing CO2 emissions and fuel consumption but also to serve as a comfort system that is able to reduce waiting times and the number of stops at traffic lights. Their performance study showed that at low traffic densities (approx. 20 vehicles/km/lane) all these goals can be reached. CO2 emissions and fuel consumption can be reduced by up to 11.5% in an ideal scenario. Waiting times even by about 17% and the amount of stops can be lowered by 6 %.

In [44] , The Authors show that the implementation of the GLOSA functionality can generally be recommended from the economical point of view. This result is achieved by applying a simulation study combined with principles of a Cost-Benefit-Analysis to a real-world demonstration site in Braunschweig. The introduction of the GLOSA functionality can generally be recommended from the economical point of view. But constraints arise by the complexity of junction signalling and approach lanes. It must be ensured that differently signalised turn flows will not overlap and thereby influence each other in a negative way. Since rising penetration rates seem to have only marginal positive effects, if at all, the speed of equipping the vehicle fleet is unimportant. In contrast, the number of traversed junctions per journey plays an important role. More investigations are needed which vehicle groups exceptionally often pass traffic signals, but it is likely that beside public transport busses commercial purpose vehicles like taxis or delivery vans are amongst them. They might also traverse a particular traffic signal more than twice a day and hence improve the Benefit-Cost-Rate further. Therefore, the market segment of commercial and fleet vehicles with a high kilometrage should be addressed first to be equipped with the GLOSA system.

In [45], authors present the results of a sensitivity analysis and identifies gear choice and the distance from the traffic light at which vehicles are informed as key influencing factors. Results indicate that a suboptimal gear choice can void the benefits of the speed adaptation. For a single vehicle and traffic light, TLA reduces fuel consumption by up to 22 % and CO, NOx and particulate matter emissions by up to 80 %, 35 % and 18 %, respectively. Furthermore, Authors identify gear choice as a significant influencing factor to the extent that a suboptimal gear choice can void the positive effects of TLA. Therefore, future applications might benefit from combining speed advice based on TLA with gear-shifting advice. For vehicles with an automatic transmission, advanced cruise-control algorithms could optimize both speed and gear choice based on TLA. As a second key influencing factor, Authors discuss the information distance, i.e. the distance at which vehicles are first informed about the traffic lights phase shifts. Evaluation shows a saturation point at about 500 m to 600 m, after which the achievable benefits become negligible compared to the technological effort (e.g. multi-hop communication). In addition, simulation results indicate that, to assess the environmental impact of TLA, the communication aspect of the simulation can be reduced to a fixed information distance. Finally, road-network simulation yields a reduction in fuel consumption of only up to 8 %. This significant difference to the result of the single-vehicle analysis indicates that the results of isolated vehicles may not be mathematically projectable to a street network, emphasizing the need of large-scale simulations of the environmental impact of TLA. Further studies, with minor outcomes, are [46] [47] [48] .

3.4 C-ITS Simulations

3.4.1 Motivation

At European level, C-ITS (Cooperative Intelligent Transportation Systems) Services are facing deployment: vehicle manufacturers have already announced to start Day One deployment of C-ITS in Europe based on ITS G5 technology during 2015 and some front runners of road operators and road authorities aim on strengthen this voluntary deployment process by investing in cooperative technologies on infrastructure side.

The most significant barrier when facing real implementation of C-ITS solutions like the one described above is related to the uncertainty of its effects in specific situations, and therefore there is the need to provide the stake-holders the evidence regarding their benefits. When it comes to networking large numbers of vehicles with a specific traffic safety or efficiency goal in mind, a portion of the traffic network with its population of vehicles has to be considered. Hence the exploration of these systems is proceeding with both field tests and traffic simulations. [58]

It though becomes mandatory the use of modelling and simulation in order to reduce costs of this process, increase the quality of products and systems, and document and archive lessons learned.

3.4.2 Related work

Simulation of C-ITS services has already been object of study since many years; for example in 2009 iTETRIS [52] implemented a large-scale integrated wireless and traffic simulation platform, by integrating integrating two widely used open source platforms, SUMO [53] and ns-3 [54] . iTETRIS project aimed to cover an existing gap in the area of cooperative ICT-based traffic management R&D through the implementation of a large-scale integrated wireless and traffic simulation platform. In fact, iTETRIS aimed to bridge the gap between the low-medium modelling accuracy and medium-large test-bed size characteristic of theoretical studies, and the high modelling accuracy low-medium test-bed size characteristic of FOTs. In this context, the iTETRIS platform is aimed at accurately evaluating the potential benefits of cooperative vehicular ICT systems to improve road traffic management under realistic conditions and large-scale scenarios, and provide indications on how the novel ICT cooperative systems should be configured and employed to maximise their potential. The simulation environment is based on software integration being designed to reduce computational costs, and allow for scalable large-scale accurate simulations.

Later on, following the same concept, the VSimRTI simulation infrastructure [55] allows the easy integration and exchange of simulators. The basic idea is to:

- Provide the flexibility to exchange simulators
- Offer the integration for arbitrary but specific simulators, e.g. for network, for traffic and environment simulators
- synchronization of and the communication among all components

- use concepts define in standards for modelling and simulations

These first approaches to simulation of C-ITS services dont include integration with real traffic management systems. When simulation activities are meant to support the design phase by ensuring transferability of results into the real world, it is necessary to adopt an in-the-loop approach. A simulation environment following this line has been proposed in ecoMove [56] , but the solution results too specific and therefore difficult to apply to other case studies. As the simulation environment is used for development support and validation of the system in ecoMove there has been choosen an in-the-loop approach. For in-the-loop testing the eCoMove System needs to be linked to a micro-simulation environment that on the one hand can model short-range communication between vehicles or vehicles and infrastructure, respectively. On the other hand, the simulation environment should allow to directly influencing the behaviour of single vehicles (global and local route choices, speed profiles). For doing so, special interfaces and adapters are needed to connect the microscopic simulator to the eCoMove System. Nevertheless, the authors themselves state that the design of the ecoMove system is too complex and therefore difficult to replicate in other situations.

Within the simTD [57] project, a similar system has been partially implemented, by including in the loop the adaptive UTC system. The simTD traffic simulation is based on a specific model framework that consists of components such as:

- a specific implementation of each simTD application,
- driver behavior based on driving simulation studies,
- optional roadside equipment,
- virtual traffic control modules, e.g. adaptive traffic signal control as required,
- a virtual representation of the underlying road network,
- traffic input and assignment according to traffic measurements on respective real roads
- a message transmission module

Even though the idea exploited in simTD it is based on similar concepts like the the work presented here, there is no use of standard message structures among the components regarding the I2V co-operative communications.

Furthermore, all existing references in literature, according to authors knowledge, refer to the DSRC I2V communication. This section presents a simulation tool-kit which represents a dedicated, practical and realistic instrument meant to support the design and implementation of a specific C-ITS solution. The flexible architecture of the simulation tool-kit allows integrating both real and simulation components.

3.4.3 COMPASS4D project, Verona Pilot Site

Compass4D pilot project is deploying cooperative ITS services in 7 European cities in order to improve road safety, increase energy efficiency and reduce congestion for road transport. In order to address these challenges, 7 cities (Bordeaux, Copenhagen, Helmond, Newcastle, Thessaloniki, Verona, Vigo), users and industrial partners are jointly implementing three cooperative ITS services: Road Hazard Warning, Red Light Violation Warning and Energy Efficient Intersection (TLA). These services are being piloted for preriods over one year of real life driving using more than 500 vehicles of different types (Busses, Heavy Goods Vehicles, Emergency Vehicles, Taxis, Electric Vehicles, Private Cars).

The project is working with local authorities, road operators, vehicle fleets and all road transport stakeholders to navigate their way to the sustainable deployment of cooperative services. Compass4D targets global harmonisation of C-ITS services and is working closely with USA and Japan.

Verona pilot site has some specific objectives besides the project ones: reducing overall delay and waiting times in traffic, reducing pollution generated by traffic density by adopting an optimum traffic strategy and positive side effects like higher comfort for road users and improvement of traffic safety.

Verona pilot site is enabling the demonstration of the Compass4D services, such as the Road Hazard Warning (RHW), Public Transport Priority (PTP) and the TLA by implementing ITS G5 RSUs at different intersections of the city of Verona for short range communication. For the first time in Europe it is testing the use of LTE for day 1 C-ITS applications, through the collaboration with the national telecom operator, who is also partner of the project. The cellular communication enables the provision of TLA service, which is covering the whole city area (circa 170 intersections).

The pilot site is leveraging from the current infrastructure based on OMNIA and UTOPIA SWARCO systems, in charge of the creation and exchange of the cooperative messages of all services. The back-office allocated to the City is hosting the Pilot Operation Management Systems (POMS) and is working closely with OMNIA, that is supporting, through the C-ITS backend, all the communication process.

3.4.4 C-ITS Simulator Overview

Components

In order to be able to perform the impact assessment of the TLA application in Verona, there was the need to develop a specific tool-kit, characterized by the following main requirements:

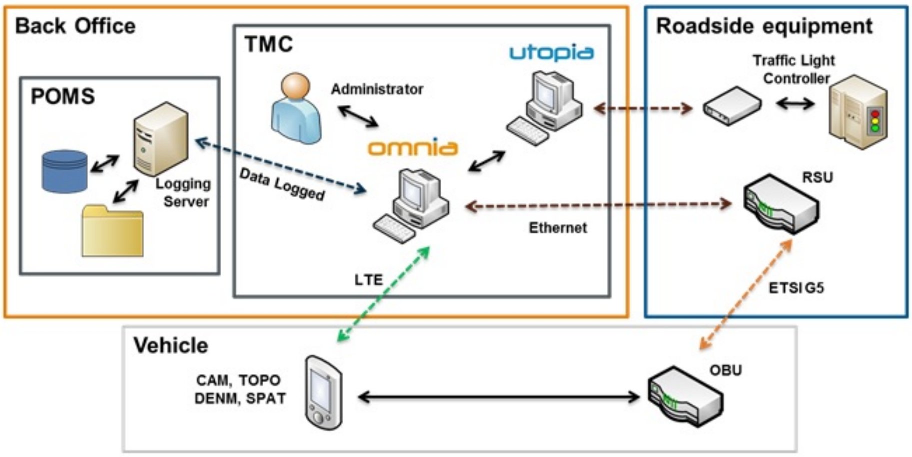

Figure 3.4. Functional architecture of the Verona Pilot Site

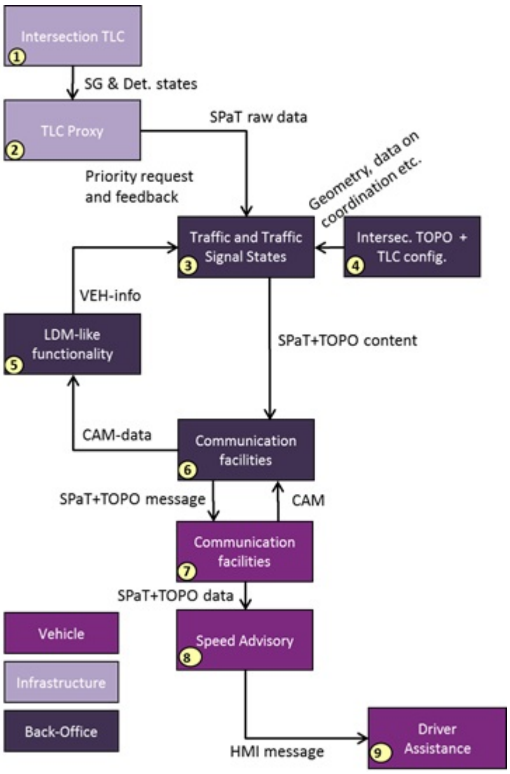

Figure 3.5. Data flow diagram for the TLA service

- An in-the-loop approach must be followed, as real SWARCO systems must be integrated:

- Adaptive UTC: There is the need to include in the loop the specific adaptive UTC system, as the actuation algorithms are owned by the industry stakeholders and therefore are confidential.
- Signal Predictor: The Signal Predictor is another key point of the TLA System, as a precise signal prediction is the fundamental aspect for the correct functioning of the system, independent of the signal controllers and of the system configuration. The algorithms present in this module, have the same profile as the ones for the adaptive UTC: they are owned by the industry stakeholders and therefore are confidential.

- Communication model must be relayed on field measurements:
  - Long range (e.g. LTE)
  - Short range (e.g. 802.11p)

Therefore, a dedicated simulation tool-kit has been developed. A generic architecture has been designed, that should be able to guarantee the transferability of the tool in other environments that exploit different systems and technologies. The C-ITS tool-kit is composed by three main components: the traffic simulation module, the TMC and the C-ITS simulation module. An overview of the generic system architecture is presented within the figure below and has been initially described in [59] .

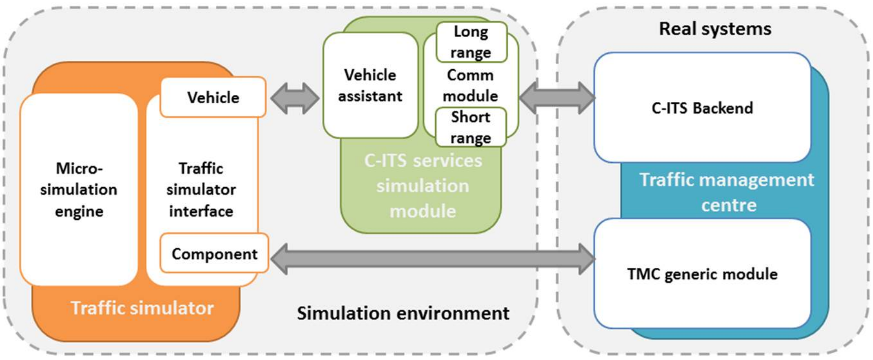

Figure 3.6. Generic system architecture for the C-ITS simulation tool-kit

TRAFFIC SIMULATOR MODULE The traffic simulation module is a software application for modeling and simulating the operation of transportation infrastructure that includes a graphic editor, a simulation engine and tools for viewing and analyzing simulation results. It includes a Simulation engine that is microscopic, stochastic and event-driven.

Microscopic simulation helps to consider each moving vehicle according to its behavior and immediate environment. The simulation model is stochastic because the parameter values (e.g. a behavioral parameter) are obtained from statistical distributions. During the simulated time period, an event (e.g. a traffic signal change) can impact a vehicles motion.

The Traffic simulator server component enables the establishment of a two-way communication between a simulation and an external program. The simulation sends the status of the detectors to the external program; this program determines the new signal state of the signals, or new speed and position of the ITS vehicles (i.e. a special class of vehicles has been defined, in order to enable the C-ITS services simulation) and sends it to the simulation. In a client-server architecture, the external program works as a server, provided the simulation works like a client.

TMC MODULE The TMC is a high level software application for the integrated road transport environment. Its modularity and scalability means that it can be successfully adopted for large-scale systems with many applications already installed as well as cities and regions at an early stage of ITS development.

For the purposes of this work, the only addressed functionality is the provision of the TLA service that aims to reduce energy use and vehicle emissions at signalised intersections, based on receiving traffic events data from the Adaptive UTC module and from the roadside equipment.

The Adaptive UTC module is connected to the Traffic simulator (exploiting the Traffic simulator server, as described in the previous paragraph) allowing the simulation provision with the real-time traffic state (for both adaptive and time-planned intersections).

The Traffic and Traffic Signal States information is being dispatched to vehicles through the C-ITS Backend module that broadcasts the SPAT message. The SPAT message includes general operational states of the traffic controller, the current signal state, the residual time of the state before changing in to the next state, the right of way for each allowed maneuver (connection between lanes) and assistance for crossing the conflict area.

C-ITS SERVICES MODULE The C-ITS services simulation module has the role of interfacing the TMC C-ITS Backend with the Vehicle and has a duplicate functionality.

The dedicated C-ITS simulator, developed (in C) for the purpose of this study, closes the Co-operative loop through the functionalities of its two modules:

- Communication module: receives the information from the Co-operative Backend of the TMC through standard data structures (i.e. SpaT message in the specific case of TLA) and applies the desired communication model (long range/ short range) by modeling loss probability and communication delays based on field measurements and, if necessary, on vehicle information arriving from the Vehicle assistant

- Vehicle assistant: interacts with the Traffic simulator, being aware of the position and speed of each ITS vehicle and influences its beahavior through applying the speed actuation. This component is also in charge of the map-matching activity, that based on the MAP message and on the position of the vehicles individuates the correspondent Signal Group.

A first version of the presented tool-kit, used for the purposes of this study, foresees the simulation of TLA service as provided within the Compass4D Verona Pilot, and is integrating Dynasim [61] traffic simulator in charge of Verona road traffic simulation, SWARCO Omnia ITS integration platform (TMC) integrating UTOPIA UTC module and a Co-operative back-end for the I2V communication. Furthermore, for closing the loop, an additional connection module has been developed: the dedicated C-ITS services simulator module.

Interfaces

TMC - Traffic Simulator The TMC is being coupled with the Traffic simulator through a TCP socket. The real UTC controllers receive simulated detectors data and return signals status to the simulation. (Frequency: 1Hz).

Two different kinds of IP interface are supported depending on the protocol implemented on the micro-simulation environment side:

- Proxy
- Controller

Proxy IP interface base on the concept of Proxy unit introduced in UTOPIA system architecture. (Proxy unit is a software application used to convert a general TCP/IP based interface between the logic controller and TLC into dedicated TLC interfaces based on serial communication and proprietary protocols.) When Proxy IP interface is implemented, the micro-simulation environment acts as a Proxy for each controller unit to be connected, providing the high level TCP/IP based interface. This configuration allows the use of micro-simulation environment or of a Proxy unit connected to a real controller in a completely seamless way from the Utopia point of view.

During operation the controller sends toward its Proxy the following data formatted in specific messages.

- Traffic Light controller commands

- Signal groups commands

The Proxy feeds-back the following information formatted in specific messages.

- (Simulated) Traffic Light controller status
- Proxy status
- (Simulated) Detectors data

Byte	Description	Length
0-3	Time (Seconds from midnight)	4 bytes
4-5	No. signal group records described in the message	2 bytes
6-7	Signal group records (0/1)	2 bytes
8-9	Signal group record length (bytes)	2 bytes

Signal group command:

*** 0 = RED**

*** 1 = GREEN 1 byte**

49 221 0 0 8 0 0 0 1 0 **0 1 0 0 0 0 0 0** 15 0

Figure 3.7. Example of status message for a TLC with 8 Signal Groups

Traffic Simulator - C-ITS Simulator In order to couple the Traffic simulator with the C-ITS Simulator, the Vehicle assistant receives information about vehicles speed and position. and updates the desired speed of the simulated vehicles according to available current prediction.(Frequency: 1Hz).

Dynasim permits establishing two-way communication between a simulation and an external program. The simulation sends the status of the vehicles to the external program; this program (in this case the C-ITS simulator) is aware the new signal state of the signals and sends to the simulation the speed advice for the correspondent vehicle.

The data exchanged from the Dynasim simulator to the cooperative services simulator is:

- Speed for each vehicle: instantaneous speed in m.s-1
- Csr location : The positions are the coordinates of the car. The referential has been defined based on Dynasim referential.

The data exchanged from the cooperative services simulator to the Dynasim simulator is:

- speed for a subset of the simulated vehicles
- the path (in a second phase it is considered the change of the routes of the vehicles)

Each transmitted information is flagged with a unique vehicle id, because this information is related to a particular vehicle. The C-ITS software is a server and the simulation is a client. This architecture has been chosen in order to be able to simulate simultaneously different flow scenarios using the same C-ITS software.

All vehicles able to communicate are reporting their position and speed every second. Following there is a simplified code example illustrating this interaction:

for ( ) {

/* Initializes the status of the Vehicle Data sent by the client (the simulation) */

/* The software is stopped and waits for Dynasim simulator to send detectors information */

DynasimServer_recCarsState(svr) ;

long numberOfCars = DynasimServer_geTnumberOfCar(svr);

for(long i = 0 ; i ¡ numberOfCars ; ++i)

long id = DynasimServer_geTidOfCar(svr,i) ;

double speed = DynasimServer_geTspeedOfCar(svr,i) ;

struct Pos id = DynasimServer_geTposOfCar(svr,i) ;

/* The C-ITS component stores this information */

}

/* Computation of the speed advice by applying the GLOSA algorithm */

DynasimServer_seTspeedOfCar(svr,id_of_vehicle, desired speed of vehicle id) ;

DynasimServer_sendCarsState(svr) ;

}

Furthermore, the C-ITS simulator provides the possibility to set some sensitive parameters that impact on the simulation process:

- Communication delay (in seconds): this parameter adds a delay to the reception of the message related to the signal phases and timings on vehicle side
- Minimum speed (in km/h): this parameter sets the minimum speed advice accepted by the driver

C-ITS Simulator - TMC For coupling the C-ITS Simulator with the TMC, the Communication module makes an HTTP request to the C-ITS Backend for the SPaT message of a specific Signal Group, based on the map-matching.(Frequency: 1Hz).

OMNIA web APIs are RESTful based web services. Web APIs are a set of methods that can be used to exchange data from/to the OMNIA environment.

Web APIs methods are grouped in two categories:

- Real time methods, that are used to exchange real-time data
- Static methods, that are used to exchange inventory related data (e.g. read objects data from inventory, add new objects to inventory, update objects data to inventory, delete objects from inventory).

All objects and methods are exposed using HTTP protocol. Object models can be serialized in XML and Json formats. Object models format can be set by the requesting client by simply specifying expected format directly into the Accept request header.

An end-point is used to get the predictions for selected intersections through the method /api/vehicleservice/spats, where the parameters of the request are determined by the intersectionid fields, with the use of use ; as separator for query multiple intersections. (i.e. The intersection to be queried is determined by the map-matching)

The picture shows an example of the prediction SPAT message, as a result of the webservice interrogation, indicating the status of the signal group and the time to change.

3.4.5 Validation framework

In order to obtain usable, realistic results from the simulation-based testing, it is required the ability to simulate each component of the system easily and accurately and also to be able to integrate smaller-scale real-world data. There is not available any standard approach to C-ITS simulations, neither consistent guidelines on the execution process, even though within the last years more and more interest it is raised on this topic. The design of this Validation Framework aims to overcome this issue by identifying the steps to be followed in order to obtain a realistic result from the simulations campaign.

The figure shows how this Validation Framework can be applied to this TLA study.

A first step contained within the Validation Framework is meant to improve accuracy of the single simulation models: the calibration. During the calibration

```xml
<Prediction>
  <IntersectionId>10001</IntersectionId>
  <TimeStamp>2014-05-20T11:09:14.6+02:00</TimeStamp>
  <Value>
      <States>
          <MovementState>
              <LaneNumbers>
                  <LaneNumber>1</LaneNumber>
              </LaneNumbers>
          <CurrentState>
              <NumberOfBits>4</NumberOfBits>
              <TrimZeroBits>false</TrimZeroBits>
              <State>0010xxxx</State>
          </CurrentState>
          <NextChanges>
          <Change>
              <MinTimeToChange>0</MinTimeToChange>
              <MaxTimeToChange>0</MaxTimeToChange>
              <LikelyTimeToChange>36</LikelyTimeToChange>
              <Confidence>0</Confidence>
              <PassState>false</PassState>
              <PredCnt>0</PredCnt>
          </Change>
      </States>
  </Value>
</Prediction>
```


Figure 3.8. Example of a prediction message

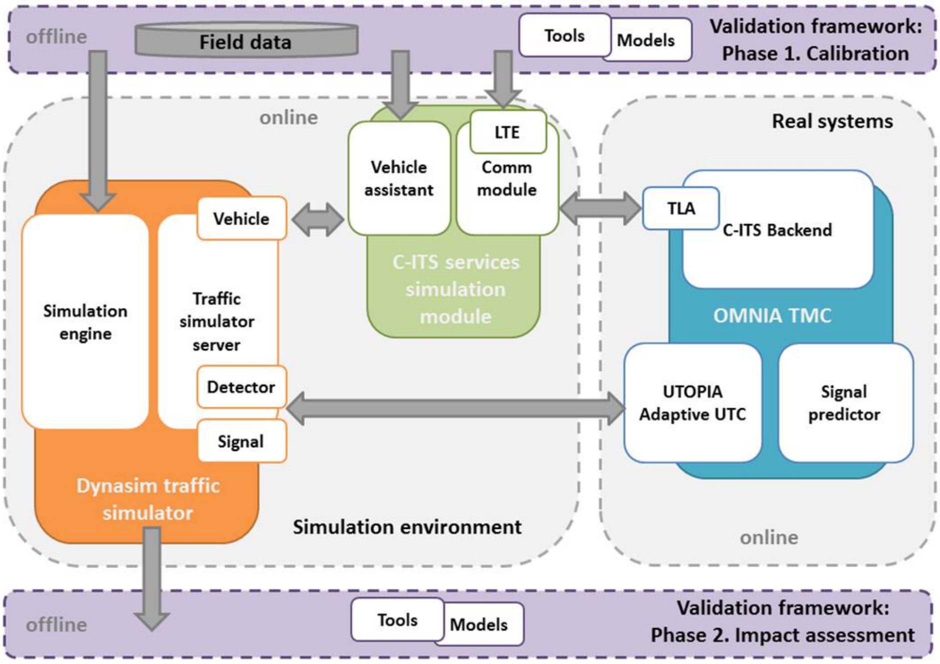

Figure 3.9. Simulation framework applied to TLA C-ITS service

phase there was the need to identify the parameters that characterize a specific ITS solution and for which mathematical modeling results weak in representing the real world and therefore needs to be completed with field data. Derived from the previous C-ITS simulation experiences in literature, the sensitive parameters are:

- The traffic model
- The driver behavior in relation to the C-ITS service
- The communication technology performances

The calibration phase was fed with real field data (obtained from traditional detectors, GPS traces and communication-related tests) and was applied for the model object of this study, in order to obtain a realistic modelling of traffic behaviour, driver behaviour and communication-related aspects.

The following paragraphs contain a summary of the calibration activities, in view of the following subsections that present each one of them, with its specificities, separately.

For the traffic model simulation a set of sensitive parameters have been chosen that have an impact on the simulation outputs. The considered performance indicator was the vehicle count. There have been defined 16 scenarios of representative values for various combinations of sensitive parameters. Multi-run simulations have been performed producing 16 values of the performance indicators. By applying a linear regression there have been derived the optimal values for the coefficients and sensitive parameters, used for model calibration.

For the driver behaviour calibration, a speed/acceleration curve has been obtained through the analysis of circa 20 GPS traces, coming from multiple users that were using the TLA applications in conditions of normal traffic flow. The parameters inside the traffic simulator have been updated according to this curve.

Regarding communication-related aspects, a simple mobile application has been implemented in order to continuously interrogate the web-service, and also load tests have been performed in order to test the performances of the system. Results show that the medium response time of the system is minor than 200 milliseconds, and therefore in this case it can be said the communication delay has no impact on the application performances.

Following the calibration phase, the impact assessment needs to be completed through comparisons among various simulation scenarios. Therefore, there was a need to individuate the sensitive parameters that impact on application performances:

- Situation of the traffic flow (soft/ normal/ rush hour)
- Penetration rate of equipped vehicles
- Communication delays in provision of the C-ITS service

3.4.6 Phase 0: The micro-simulation model definition

The microsimulation model object of this case study considers a stretch of road in Via Goffredo Mameli, Verona, Italy, covering 4 junctions (1km long). The distances among the intersections are of circa 300m each.

Figure 3.10. Test area in Via Goffredo Mameli, Verona

The choice of the model has been made due to its characteristics, that made it perfectly adapted to the case study:

- SWARCO Adaptive UTC system available in the area
- TLA service available due to ongoing R&D initiatives
- TLA mobile app available due to Compass4D
- Log for TLA mobile app available (GPS traces, speed) within Compass4D
- Free access to local systems/ DBs (e.g for example in order to obtain vehicle counts from the loop detectors in the examined area) due to collaboration with Verona City in project Compass4D
- 1 year of operation (2015) that permits the collection of a high amount of field data
- Cca. 500 users expected within Compass4D

3.4.7 Phase 1: Model calibration

Traffic

Microscopic simulation models have been widely used in both transportation operations and management analyses because simulation is safer, less expensive, and faster than field implementation and testing. While these simulation models can be advantageous to engineers, the models must be calibrated and validated before they can be used to provide meaningful results for a specific model. The method for the traffic calibration was found in literature [60] and applied to the present case study.

In the first step, one has to determine a performance measure and identify uncontrollable input parameters and controllable input parameters. Therefore, a set of sensitive controllable input parameters that impact on car-following rules have been chosen that have an impact on the simulation outputs:

- Car reaction time (s)
- Extreme lane change distance (m)
- Mandatory lane change distance (m)
- Light vehicle minimum distance (m)

The second step was to identify the performance indicators. In the present study, the considered performance indicator was the vehicle count, as this is the unique information available from the field.

There have been defined 16 scenarios of representative values for various combinations of sensitive uncontrolable input parameters defined in the first step. Multiple run simulations (2 runs/ scenario) have been performed producing 16 values of the performance indicators.

By applying a linear regression there have been derived the optimal values for the coefficients and sensitive parameters, used for model calibration. Candidate parameter sets were created with the linear regression model. Microsoft Excels Solver was used to obtain candidate parameter combination sets.

In order to validate the choice of the parameters, the simulation was performed again on three random scenarios and results showed a difference minor than 0.05% respect to the field derived performance indicator.

The obtained values for the sensitive input parameters are:

- Car reaction time: 1,5s
- Extreme lane change distance: 1m
- Mandatory lane change distance: 180m
- Light vehicle minimum distance: 4m

Driver

The idea for the calibration of the driver behavior derives from the fact that Dynasim permits to insert, as a parameter of the simulation, the speed/acceleration curve for the simulated vehicles. In order to determine this curve based on field results, 20 GPS traces have been analysed. Different drivers were using the GLOSA application in conditions of normal traffic flow.

Figure 3.11. GLOSA APP in Verona

The speed/acceleration curve derived from field tests, used for calibration is shown in the figure below:

Communication

Though the public stated performances for the LTE network are more than acceptable when dealing with a C-ITS efficiency service like TLA, for the completeness of this study some investigations were performed on both communication and TLA web-service performances.

In order to test the field communication profile in the city of Verona, a simple android APP was developed and RTT values were registered both during labor days and during holidays.

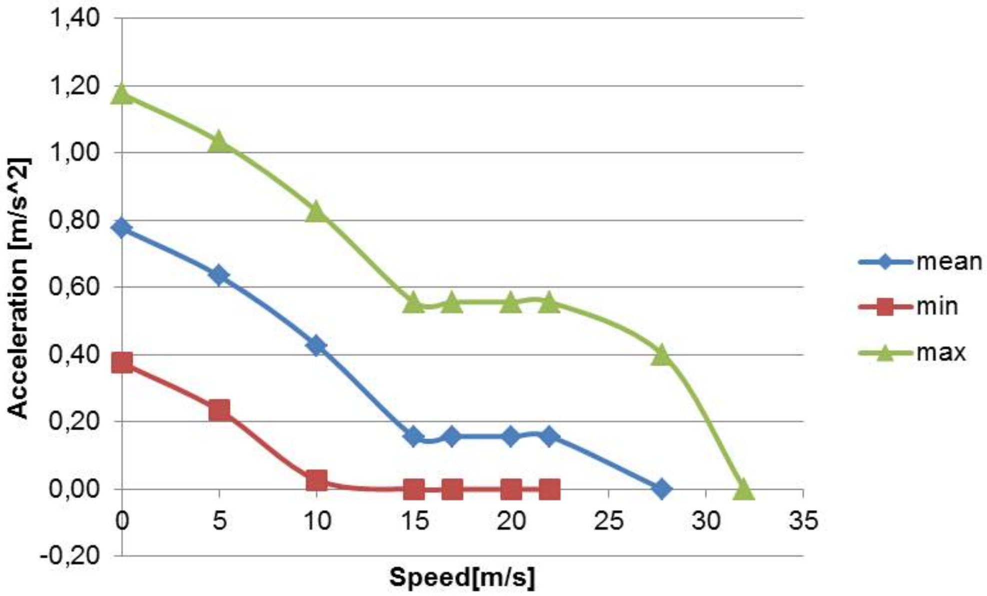

Figure 3.12. Speed/acceleration curve for driver behavior calibration

Results derived from circa 20.000 test values showed that in both cases, the RTT is under the threshold 250ms, which is more than sufficient in order to guarantee the performances of the applications.

Moreover, the webservice has been tested using the SoapUI tool [62]. Tests have been realized by implementing 500 concurrent requests (500 is the expected number of users in Compass4D). Registered RTT values were below 200ms during the load test.

Therefore, it can be said that in this case the communication related aspects have no impact on the application performances.

3.4.8 Phase 2: Application impact assessment

Confidence interval

In order to determine the confidence interval of the simulation results, 19 runs were realized by simulating the same scenario using different seeds.

From the analysis of the obtained values (i.e. the analysis was performed on the cumulative stop time value), resulted considering a level of confidence of 95% the approximate CI is [MEAN VALUE-0.93%,MEAN VALUE+0.93%].

Based on these results, for the completion of the simulation campaign, only one run was performed for every scenario, mainly due to the long simulation times (1

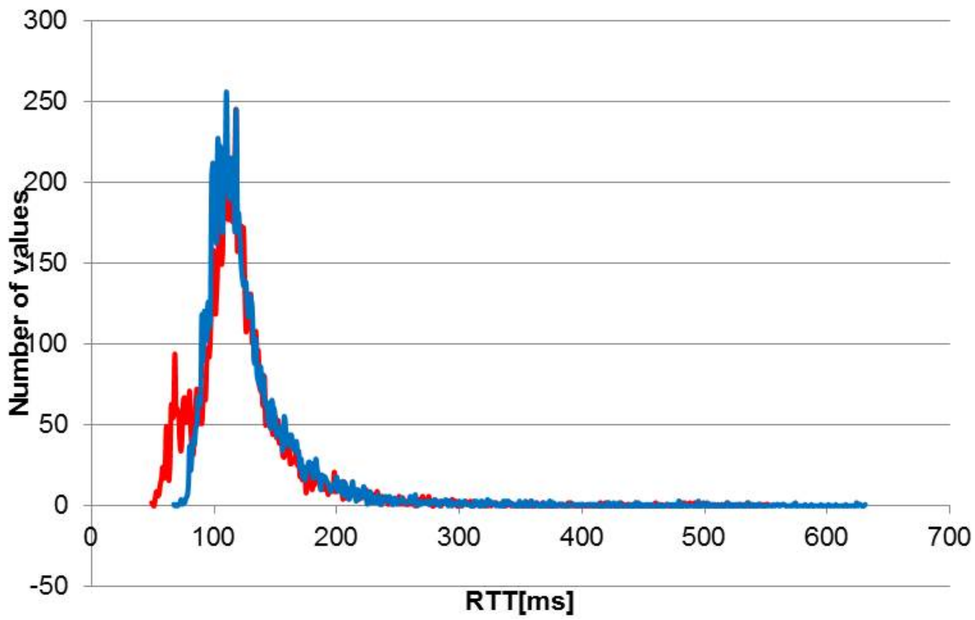

Figure 3.13. RTT values distribution for labour days (blue) and holidays (red)

minute of simulated time = 1 second of real time).

Definition of the simulation scenarios

In order to perform the impact assessment, various scenarios were simulated. A selection of sensitive parameters has been defined and their correspondent values:

- Traffic flow
  - Low (soft hour)
  - Normal
  - High (rush hour)
- Information delay
  - Less than 1 second
  - 3 seconds

  Even though it was stated that communication related aspects have no impact on the application performances, it has been chosen to investigate on the impact of erroneous information at vehicle side. This is due to the fact that when involving predictions for isolated intersections, delays of information may occur.

- Penetration rate of equipped vehicles
  - Baseline (0% of C-ITS vehicles)
  - 20% of C-ITS vehicles
  - 50% of C-ITS vehicles
  - 50% of C-ITS vehicles

Definition of the performance indicators

Performance indicators for the impact assessment on both the driver and the municipality have been defined, as follows:

- Travel Times for crossing the defined sub-network
- Stops per Time Unit (direct impact on fuel consumption)
- Number of stops per vehicle within the defined sub-network
- Duration of stops per vehicle within the defined sub-network
- Traffic flow within the defined sub-network

Results

Results presented in this section derive from a simulation campaign conducted according to the methodology presented in previous paragraphs from various combinations of the sensitive parameters. The duration of each simulation is 30 minutes, with a 15 minutes time for the assessment of the traffic flow.

In conditions of normal traffic flow (500 up to 700 vehicles/ hour) the TLA application produces an equilibrate benefits for both driver and road operator. It is interesting to notice that with increasing the number of equipped vehicles optimizations are perceived at both driver side as municipality side.

In conditions of low traffic flow (100 up to 200 vehicles/ hour) the TLA application produces an effect even with a reduced number of equipped vehicles, but it could be stated that there is no significant benefit registered. It is interesting to notice that travel times tend to increase. This is due to the fact that in most cases the GLOSA application would decrease the overall speed, in order to permit the crossing of the intersection with a greenlight and generally make the journey smoother.

In conditions of high traffic flow (1000 up to 1200 vehicles/ hour) the TLA application produces mostly a benefit for the municipality. It is interesting to notice that, even in situation close-to-congestion, and even if this application, as explained

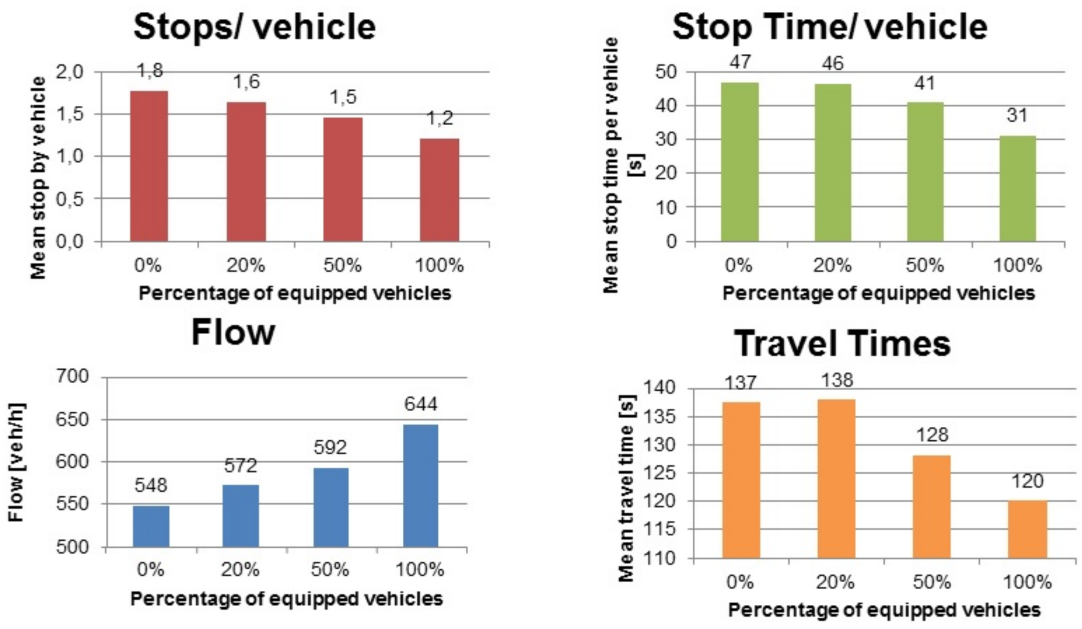

Figure 3.14. TLA application performances in conditions of normal traffic flow

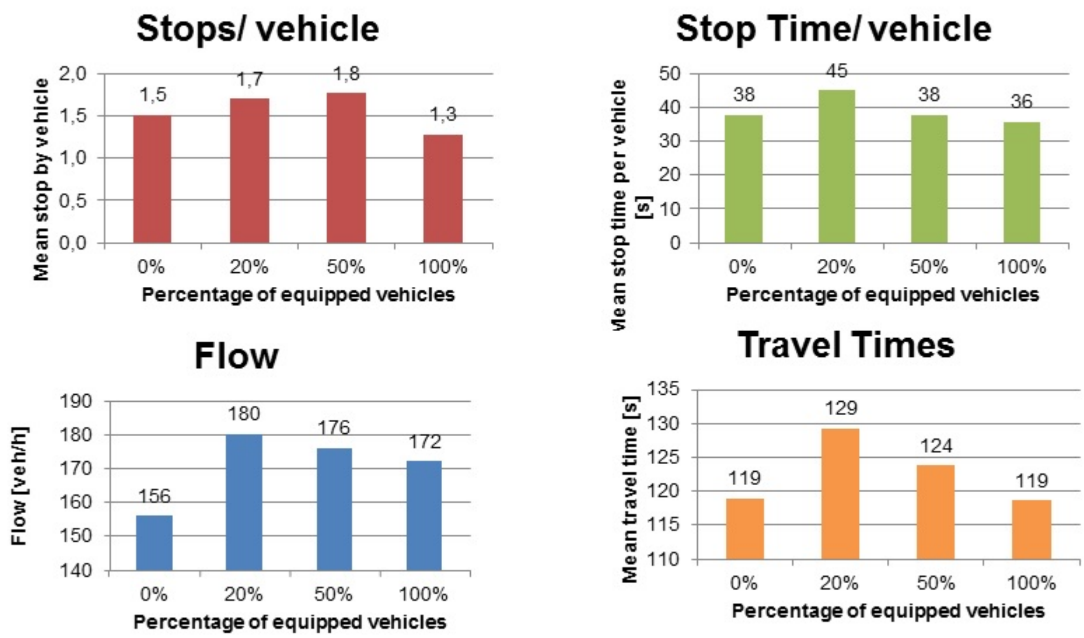

Figure 3.15. TLA application performances in conditions of low traffic flow

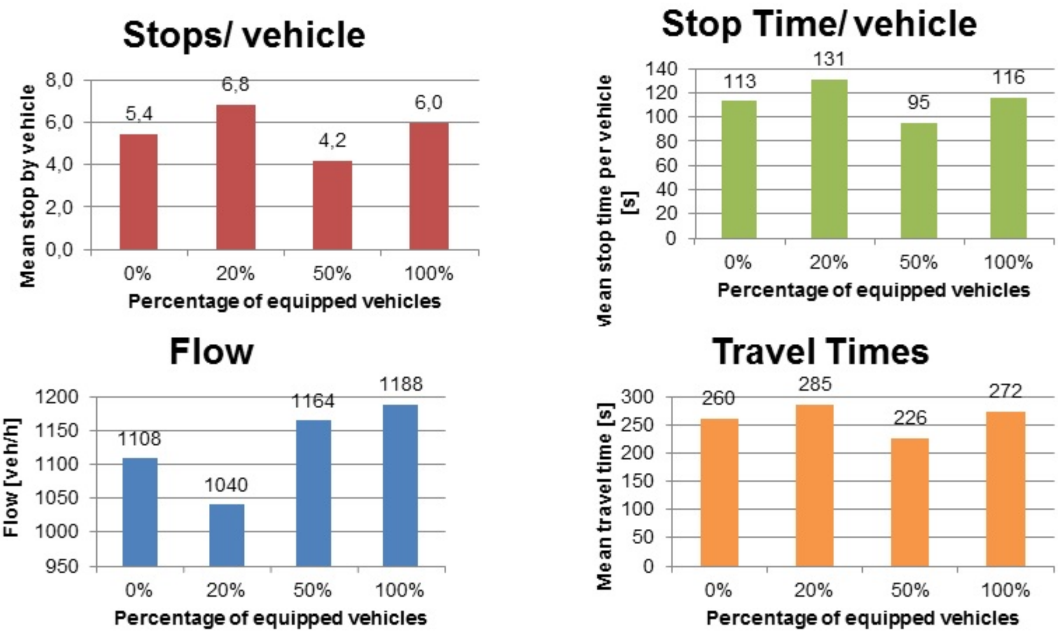

Figure 3.16. TLA application performances in conditions of high traffic flow

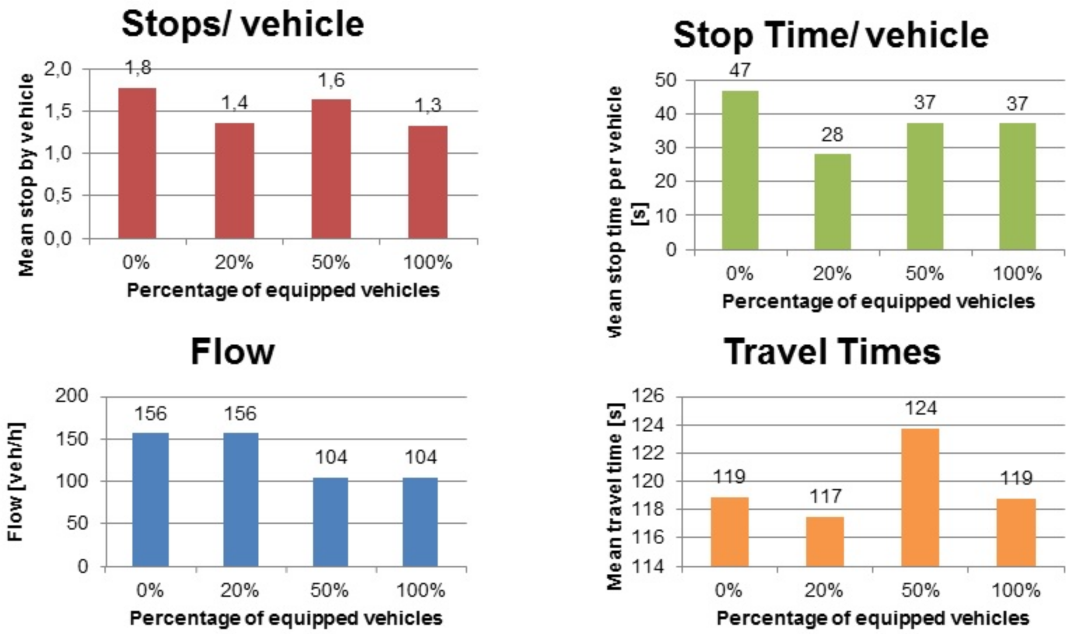

Figure 3.17. TLA application performances in conditions of normal traffic flow, with an information delay

before, is overlapping with the actuation of the Adaptive UTC, the TLA application produces a considerable effect on the traffic flow, by increasing it with 15%.

As mentioned in the introductive part, in case of integrating isolated intersections a major challenge of the Signal Predictor is to avoid erroneous prediction. Results clearly show that such errors (in this case a constant delay of 3 seconds has been applied) would generate a traffic situation which results to be nearly worse than the baseline situation. This result is fundamental in order to highlight the fact that the performances and the precision of the TLA systems are fundamental for the application success.

3.4.9 Personal contribution

The personal contributions of the candidate, developed within this PhD experience, are related to following activities:

- Compass4D project level
  - Technical management of Verona and Thessaloniki pilot activities
  - Architectural design of implemented C-ITS solutions
- Compass4D simulation activities
  - System architectural design
  - Simulation tool-kit
  - Interfaces among components
  - Development of C-ITS simulation module (in collaboration with Dyna-logic)
  - Validation framework conceptual design
  - Field testing (e.g. Android app for communication-related tests)
  - Model implementation
  - Calibration and validation of the simulation tool-kit
  - Impact assessment for the TLA application (Verona Case Study)

3.4.10 Considerations on application performances

Before getting to the conclusions on the impact assessment of the TLA application there is the need to draw the attention on three observations:

- The distance among intersections not optimal (literature indicates a distance major than 500m among intersections in order to obtain optimal results)

- There might be an influence of the reduced simulation time for each scenario: 30 minutes (given the fact that the travel time along the sub-network is in the worst case around 5 minutes, it was considered sufficient for the purpose of the study)
- Adaptive traffic control already optimize the traffic conditions (an estimation for SWARCO Adaptive UTC performances indicate an average travel time savings of 16% while peak hour savings are 30%)

Nevertheless, the most significant results show that in conditions of normal traffic flow conditions the TLA application produces an equilibrate benefits for both driver and road operator. The optimization of driving and traffic conditions are highlighted by the results below:

- -32% Stops/ vehicle
- -34% Stop Time/ vehicle
- +18% Traffic Flow
- -12% Travel Time

While in high traffic flow conditions, benefits for the road operator are being registered (up to 15% of increased traffic flow in case of 100% of equipped vehicles), in low traffic flow conditions there are no relevant benefits, as expected.

An important conclusion for the deployment phase of TLA, meant to sensitise the attention of both users and municipalities, is that results clearly show that a high penetration rate of equipped vehicles is needed in order to obtain benefits in all traffic conditions.

3.4.11 Conclusions and future work

This work has presented an approach to simulation for the C-ITS services, derived on literature studies and best-practices, based on two innovative aspects: (i) integration of the real adaptive traffic light control/ signal predictor modules in the simulation loop and (ii) a validation framework containing a calibration phase based on real-life measurements. Furthermore, the tool makes use of standard data structures for C-ITS.

The major drawbacks of the presented solution are related to (i) transferability of the tool-kit to other systems (as it is highly dependent on the Traffic simulator and Adaptive UTC interfaces, as they don't follow any standard) and (ii) high simulation timings: 1 minute simulated time = 1 minute.

Nevertheless, according to actual trends in C-ITS, realistic simulation environments will represent in the near future a key element in the design process of large-scale C-ITS solutions.

As a future work, a first step will be to apply the method to various typologies of models, in order to be able to perform a wider impact assessment of the TLA application. A second issue to be addressed is related to the extrapolation of the results, from intersection level to network level.

Chapter 4

Conclusion

The research activity during this PhD period was concentrated on two complementary aspects in ITS: Data acquisition and Data diffusion.

A first part of the research activity was focused on WSN for Road Infrastructure Monitoring involving the use of a prototype system designed for road side applications based on an advanced dedicated radio protocol in ISM band (2.4 GHz) for linear topology WSN. The work was focused on the analysis and validation of the proposed scheme, in relation to three road-side applications: indoor localization in road tunnels, traffic monitoring in highway environments and intelligent public street lighting in urban areas.

Using a WSN-based approach for road infrastructure monitoring, opens innovative application scenarios: the possibility of having a large number of acquisition devices that placed at short distances between them allow precise collocation of an event in terms of time and space, with high flexibility of the monitoring network. In the same time, using energetically efficient elaboration and transmission techniques makes sensors independent in terms of power-supply (a small photovoltaic panel could be sufficient as a power-supply source) and using radio transmitting system allows dispensing a transmission network connection, reducing installation and maintenance costs. Scalability issues are still to be addressed as a future work.

These considerations, along with results and feedbacks achieved from pilot installations show how the developed prototype WSN represents a promising solution for ITS safety/control applications that features (i)low power, (ii)low cost and (iii)low maintenance - combination that represents the strength of the proposed solution respect to other existing ones.

The second part of the research activity addresses the complementary aspect in ITS related to the diffusion of the information towards the final user, in particular the I2V Communication for the provision of TLA service, already active on the field. The presented work is related to the realization of a simulation tool-kit for the impact assessment of TLA meant to support the design phase and the marketing activities for C-ITS solutions.

It has been defined a simple generic architecture for the simulation of C-ITS services characterized by two innovative aspects: (i) the integration of the real adaptive traffic light control/ signal predictor modules in the simulation loop and (ii) the definition of a validation framework containing a calibration phase based on real-life measurements. Furthermore, the tool makes use of standard data structures for I2V communication.

According to actual trends in C-ITS, realistic simulation environments like the one deployed in this work will represent in the near future a key element in the design process of large-scale C-ITS solutions.

An impact assessment procedure has been carried for the TLA application on a stretch of road in Verona and results show how the application produces benefits for both the driver and the municipality, mainly in normal traffic conditions. A high penetration rate is fundamental for the complete success of the application.

In closure, a final consideration: the work described in this document has been performed at application level. The results have a significant value especially from the industry point of view as they mainly address sensitive topics/systems/prototypes in pre-deployment phase present within the SWARCO reality. Furthermore, all results derive from field installations in realistic environments, by exploiting the academic know-how through its application in industry environment - the initial aim of the collaboration that put the bases of this research activity.

Appendix A

Acronyms

2-FSK: Binary Frequency Shift Keying

AID: Automatic Incident Detection

AFB: Active Folded Bus

AOA: Angle Of Arrival

CAM: Co-operative Awareness Message

CI: Confidence Interval

C-ITS: Co-operative Intelligent Transport Systems

CRC: Cyclic Redundancy Code

DAMA: Demand Assigned Multiple Access

DENM: Decentralized Environmental Notification Message

DSS: Decision Support System

DSSS: Direct Sequence Spread Spectrum

FEC: Forward Error Connection

FHSS: Frequency Hopping Spread Spectrum

FSM: Finite State Machine

GLOSA: Green Light Optimized Speed Advice

GFSK: Gaussian Frequency Shift Keying

I2V: Infrastructure To Vehicle

IEDG: Isolated Event Detection Grape

IP: Internet Protocol

ISM: Industrial, scientific and medical

ITS: Intelligent Transportation Systems

IU: Informative Units

LED: Light Emitting Diode

LTE: Long Term Evolution

MSK: Minimum Shift Keying

OBU: On Board Unit

PDU: Protocol Data Unit

PLR: Packet Loss Ratio

RP: Radio Packet

RSSI: Received Signal Strength Indicator

RSU: Road Side Unit

RTT: Road Traffic Telematics

RTT: Round Trip Time

SPAT: Signal Phase And Time

SNR: Signal-to-Noise Ratio

TCC: Traffic Control Centre

TMC: Traffic Management Centre

TLA: Traffic Light Assistant

TLA: Traffic Light Controller

TOA: Time Of Arrival

TDOA: TimeDifference Of Arrival

UTC: Urban Traffic Control

VMS: Variable Message Sign

WEDG: Wireless Event Detection Grape

WSN: Wireless Sensor Networks

WWD: Wrong Way Driver

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