AN 802.11P COMPLIANT SYSTEM PROTOTYPE SUPPORTING ROAD SAFETY AND TRAFFIC MANAGEMENT APPLICATIONS

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Abstract: - During the last decades Intelligent Transportation Systems (ITS) have been attracting the interest of an increasing number of researchers, engineers and entrepreneurs, as well as citizens and civil authorities, since they can contribute towards improving road transport safety and efficiency and ameliorate environmental conditions and life quality. Emerging technologies yield miniaturized sensing, processing and communication devices that enable a high degree of integration and open the way for a large number of smart applications that can exploit automated fusion of information and enable efficient decisions by collecting, processing and communicating a large number of data in real-time. The cornerstone of these applications is the realization of an opportunistic wireless communication system between vehicles as well as between vehicles and infrastructure over which the right piece of information reaches the right location on time. In this paper, we present the design and implementation of representative safety and traffic management applications. Specifically we discuss the hardware and software requirements presenting a use case based on the NEC Linkbird-MX platform, which supports IEEE 802.11p based communications. We show how the functionality of IEEE 802.11p can be exploited to build efficient road safety and traffic management applications over mobile opportunistic systems and discuss practical implementation issues.

Key-Words: - Intelligent Transportation Systems, Vehicle-to-Vehicle networking

INTRODUCTION

Road safety, air pollution and traffic management are three major concerns that the residents of urban centers around the world have to face promptly given the radical growth in cities’ population. Road traffic accident mortality is high among young people with transport accidents causing 8\% of all loss below 65 years in the EU-27 [1], more than any disease. Across European Union (EU), transport is most dangerous in regions in Portugal, Lithuania, Latvia, Corsica, Greece and Poland. While road traffic injuries are a major cause of death and disability globally, a disproportionate number occur in developing countries. Road traffic injuries are currently ranked ninth globally among the leading causes of disability adjusted life years lost, and the ranking is projected to rise to third by 2020. In 1998, developing countries accounted for more than 85\% of all deaths due to road traffic crashes globally and for 96\% of all children killed [2], [3]. On the other hand, air pollution is tightly related to traffic management and plays a substantial role to the climate change while burdening the commitment of Europe to decrease the CO2 emissions. In urban areas, an increase in average speed may dramatically reduce fuel consumption, while traffic signal synchronization has the potential to increase intersection throughput for private traffic by 15\%. Guiding traffic (e.g. through route advisory systems) away from problematic areas may lead to up to 8\% less emissions [2]. Today, 30\% of energy is consumed for transportation of humans and goods [5] and circa 18\% of the CO2 emissions from combustion coming from road transportation [6]. Although the broadening of the road infrastructures increases their capacity, it cannot keep up with the pace of the increase in urban populations worldwide, due to cost and time reasons, leading the city authorities to pursue “soft” measures to solve the problem [7]. Furthermore, there are many efforts by the scientific community to combat many critical issues that hold back the vehicular network’s deployment but also support the Intelligent Transportation Systems (ITS) development by performing standardization efforts concerning vehicular communications [8], [9].
To tackle the previously reported issues and problems, the design and development of ITS has been pursued extensively in the last decade. These systems rely on intelligent collection and processing of information which enables decision making and information/decision dissemination to enhance the citizen’s experiences either through enhancing transportation efficiency or safety. They can be classified in advanced public transport systems, advanced traveler information systems, advanced Traffic Management Systems, incident management systems, electronic toll collection systems, Vehicle Information and Communications System and Video Transmission Systems for road surveillance. ITS are expected to play a major role in enhancing road safety, transportation efficiency and improving environmental conditions, both in developed as well as in developing countries as mentioned above. Their impact will be critically affected by the adoption of standardized and low-cost technologies that can result in massive production of commodity hardware components and wide deployment of interoperable systems.

The common denominator of the realization of all these systems is the effective communication between vehicles and infrastructure enabling real-time information collection and dissemination following a distributed architecture. While initial attempts assumed WLAN communication, IEEE has standardized the 802.11p protocol and the 1609 standard family comprising the Wireless Access in Vehicular Environments (WAVE) standards in order to define the architecture, communication model and mechanisms of high-speed short range wireless low latency communications. The original IEEE 802.11, intended for WLAN, has two drawbacks within its MAC technique CSMA; it can cause unbounded delays before channel access as well as collisions on the channel. The IEEE 802.11p, also known as Dedicated Short-Range Communication (DSRC), is intended for vehicular ad-hoc networks (VANETs). Currently this is the only standard with support for direct vehicle-to-vehicle (V2V) communication [10], [11]. Other early systems based on mobile communications e.g. 3G combined with GPS systems could only offer limited location based services, without being able to offer broadband services as well as vehicle-to-vehicle communications with real-time response which are critical for supporting traffic management and road safety applications over a single system.

In this paper, we present a practical use case based on IEEE 802.11p implementing applications targeting road safety and traffic management over mobile opportunistic systems. We consider a generic architecture where mobile nodes (equipped with On-Board Units - OBUs) with sensing capabilities are opportunistically connected to each other and to static nodes located at the roadside (Road Side Units - RSUs) using the IEEE 802.11p standard. We present applications that can be designed and implemented on this architecture towards enhancing the road safety and traffic management efficiency. We also discuss the advantages and the feasibility of the approach as well as we explore critical aspects for the wide penetration of such systems.

The rest of the paper is organized as follows: in section 2 we present the considered Vehicle-to-Vehicle and Vehicle-to-Infrastructure communication architecture, while in section 3 we briefly outline the IEEE 802.11p functionality that will be exploited for the application development. In section 4 we design application capitalizing on this architecture related to both the city traffic cycle and a highway case. In section 5 we discuss practical aspects of the application development as well as issues with respect to the promotion of these applications. Finally, conclusions and future work are drawn in section 6.

**NETWORK INFRASTRUCTURE SUPPORTING MOBILE OPPORTUNISTIC COMMUNICATIONS**

The vehicular networks can be classified into two main transmission types, Vehicle-to-Vehicle (V2V) communication among vehicles and Vehicle-to-infrastructure (V2I) communication between a vehicle and the infrastructure which is a fixed unit generally located at the roadside [12]. In this work, we consider the system architecture that is depicted in Figure 1. Vehicles with and without “on board units” travel on the road. The “on board units” (called hereafter OBUs) consist of a system equipped with sensing devices (e.g. humidity sensor, temperature sensor, accelerometer, gyroscope, CO₂ sensor) and with a device capable of communicating either with other vehicles or with devices installed in the road (infrastructure) side. A Road Side Unit (called hereafter RSU) is capable of communicating (apart from the vehicles in their transmission range) with an application server located at the premises of the traffic management or road operation authorities through any legacy wired or wireless communication technology. We consider that such devices can be attached to traffic light posts or posts carrying either lights or cameras in highways where access to power and communication networks is provided.
For the communication between the vehicles and between the vehicles and the infrastructure we rely on the IEEE 802.11p protocol which supports wireless communication between nodes moving at high speed. Short-range wireless communication based on IEEE 802.11 is characterized by low cost, availability and wide deployment. The wireless technology enables a fully distributed vehicular communication network based on self-organization and self-coordination of the network nodes which is mandatory for car-to-car and car-to-infrastructure communication (called Car-2-X or shortly C2X by NEC in [13]). The transmission occurs in the 5.9 GHz unlicensed band for both EU and USA with a maximum transmission range of 1000m with 200μs latency and a data rate between 6-27Mb/s.

![Figure 1: The system architecture](image)

While car manufacturers install more and more sensors on the vehicles and offer more and more communication interfaces (e.g. Bluetooth, USB), they are reluctant to disseminate the sensor readings (even for a very limited subset of the available sensors). To partially address this issue the US Environmental Protection Agency (EPA) standardized the On-Board Diagnostics (OBD) interface. OBD systems are designed to monitor the performance of some of an engine's major components including those responsible for controlling emissions. There can be over 300 readings available, depending on the vehicle manufacturer and model. However vehicles vary in the readings they will support and scanners vary widely in the number of these signals that they can read. Hence proprietary interfaces tend to increase the cost for customization of sensor reading systems per vehicle type and additionally sensors critical for a variety of applications (e.g. GPS) are not standard equipment and may not be available. On the other hand, the cost of sensors decreases rapidly as the production volumes constantly increases. In this view, the development of a single device (OBU) that supports communication based on IEEE 802.11p and that is equipped with a small set of sensors and possibly a display (for communicating with the driver) to implement road safety applications at low cost seems a realistic solution. Statistics show that European citizens are highly interested in safety when buying a car and thus it is highly likely for them to be also interested in buying a device that supports safety applications. In the future leveraging technology consolidation, market adoption and mature (potentially open) interfaces, such a device could be combined/embedded with devices offered by highway operation authorities for electronic toll payment (e.g. e-pass) or automotive control systems. These devices could also support entertainment applications which may offer further incentives for installing such a device in the vehicle even for young drivers who may underestimate safety or traffic management benefits. For example, offering instant messaging with passengers of nearby cars for free could strengthen the incentives. Following this trend, an application for dynamically adapting traffic light timing initially adopted for specific vehicle types, (e.g. for providing priority to ambulances or public transport means) was deployed in Albacete, Spain ([14]) albeit using OBUs that communicate over WLAN technologies. In India respectively, in a bid to keep vehicle drivers from violating traffic rules, the Pune Municipal Corporation (PMC) will be sharing traffic violation data with insurance companies. Through this, insurance players will be able to understand if the accident has happened due to any
kind of violation of traffic rules. These initial deployments, as well as several others globally demonstrate the increasing adoption of smart applications over ITS to enhance safety and transportation efficiency.

In this paper, we consider the case where OBUs integrate a microprocessor and memory elements with the following limited set of sensors:

- Geographical Positioning System (GPS), which provides geographical references, speed and direction information. Such data are required by the IEEE 802.11p standard (i.e. to support node identification and implement geographical routing) as well as to support applications that depend on the detection of direction or speed changes to provide early warning signals and prevent accidents to moving users.
- Humidity and temperature sensors, to enable the detection of severe environmental conditions that may need specific action taking.
- Peripheral devices for informing the driver (e.g. display or audio peripherals)

For experimental purposes, such an OBU device was developed using the NEC Linkbird-MX device [7] connecting to it appropriate external sensors through USB interfaces. Should car manufacturers open part of the car sensor network to third parties, OBUs could be equipped with an additionally interface to communicate with the car sensor network, if this brings reliability or cost benefits.

For the RSU, it is important to support IEEE 802.11p functionality to communicate with the vehicles and another communication technology (wireless or wired) to connect to a server that is capable of processing real-time information and implement intelligent decision making schemes. RSUs execute a multitude of functions including forwarding of data (to increase the coverage of the ad hoc network), transmission and reception of application data from the vehicles (e.g. collecting measurements and disseminating warnings or decisions made at the Traffic Control Center – TCC), communication with the road operation authorities and traffic control center and Internet access support to cars. Furthermore, the RSU could be equipped with sensors (e.g. for weather or CO₂ emissions monitoring) and deliver the readings to decision making applications.

Exploiting the above architecture, the drivers of all the vehicles, the pedestrians and the road operation authorities can benefit from the sensed data. This architecture comprises a distributed sensing infrastructure (sensing overlay) since the vehicles are capable of detecting events and through their opportunistic communication with the RSU, the sensed data can arrive at the road operator and/or traffic management authorities. This distributed infrastructure senses the whole road network, even neighbourhoods or areas where the traffic does not justify investment on monitoring infrastructure. On the other hand, the routing instructions and traffic information can be disseminated towards both pedestrians and drivers through a variety of means which includes (apart from the OBU), variable message signs and mobile phones to reach a wider audience.

THE IEEE 802.11P NETWORKING FRAMEWORK AND PROTOCOL STACK

The requirements imposed by vehicular communication for support of highly mobile vehicles, frequent topology changes, and scalability with potentially very large number of nodes dictated the adoption of geographical routing principles [16], which can be secured [17] with limited node resource consumption and has been proven to have good performance not only on simulated but also in realistic environments [22]. Therefore, the 802.11p Task Group of IEEE has chosen the so-called Geocast routing protocol as the core networking protocol for vehicular communication. IEEE 802.11p is an approved amendment to the IEEE 802.11 standard promoted by the Car-to-Car Communication Consortium (C2C-CC) in Europe, the major European industry consortium for vehicular communication. This protocol supports opportunistic communication as well as multi-hop communication supporting both a) the forwarding of data towards the geographical position of a single destination node for unicast communication and b) the distribution of data in a geographical region.

The Geocast is an ad hoc routing protocol utilizing geographical positions for data transfer. It is assumed that each vehicle is aware of its geographical position via e.g. GPS and periodically advertises this information to its neighboring vehicles (in the so called beacon messages). Hence, an IEEE 802.11p enabled device is informed about all other IEEE 802.11p devices located within its direct communication range (one hop neighbours) and maintains a so called neighbor table in soft state containing all known neighbours IDs and their geographical positions.

Geocast supports point-to-point and point-to-multipoint communication. Leveraging the capabilities to distribute information based on geographical routing, enables innovative applications mainly by exploiting the
protocol capabilities for selective addressing of geographical areas as target of data packets. Thus, a vehicle can specify a well delimited geographic area to which the messages should be delivered/broadcasted. Intermediate vehicles serve only as message relays and only the vehicles located within the target area terminate messages at the application layer conveying related information to the driver as appropriate. In this way, the vehicles that are actually affected by a dangerous situation or a traffic-related event are notified, whereas vehicles unaffected by the event are not targeted. The geographical area can be rectangular, circular or ellipsoidal. To this end the following forwarding types of Geocast can be used:

- GeoUnicast, which is a unidirectional data transport service from a single source node (S) to a single destination node (D) (Figure 2a). Node S forwards data packets to the one-hop relay node (F) that is closest to the destination, which in turn forwards them along the path until they reach the destination node D.

- Geographically-Scoped Broadcast (GBC), which is used to transport data from a single node to all nodes within a user defined range and area (either via unicast as shown in Figure 2b or other other forwarding methods like the Contention-Based Forwarding CBF).

- Topologically-scoped broadcast (TSB), which provides rebroadcasting of a data packet from a source to all nodes in a limited N-hop neighborhood (Figure 2c), which can reside at a distant geographical area. Single-hop broadcast is a specific case of TSB which is used to send periodic messages (beacons or heartbeats), while setting N large enough so as the whole ad hoc network can be reached. TSB shall be used very rarely since it may cause network congestion.

APPLICATIONS ENHANCING SAFETY
Leveraging the IEEE802.11p mechanisms for realizing efficient communication between mobile nodes and between mobile and static nodes (C2X communication), the next step is the design and implementation of intelligent applications than enhance road safety and assist traffic management. In the sequel, we present the following intelligent applications that can be implemented in the vehicular environment.
indicative applications that capitalize on the considered architecture. The applications we implemented exploit the communication network described above comprising the in-vehicle, ad hoc, and infrastructure domains. The ad hoc domain is composed of vehicles equipped with OBUs and stationary RSUs that can be attached to fixed locations. Most prominent locations for RSUs include traffic lights and Variable Message Signs (VMS). RSUs are responsible for interconnection between the ad hoc and the infrastructure domain. Thus, OBUs can directly communicate if direct wireless connectivity exists. In case of no direct connectivity, multi-hop communication is used, where data is forwarded from one OBU to another, potentially via RSUs, until it reaches its destination. By deploying this kind of ITS infrastructure prototype fixed service-based cooperative information systems have been developed and tested [18].

City Traffic management based on distributed sensing
The traffic lights consist a key element in traffic management within a city. The coordinated traffic flow control implementing the “green wave” concept [19] was initially proposed to minimize the vehicle stops to red traffic lights within the city. The rationale is that reducing unnecessary stops and increasing the average transportation speed of vehicles reduces both the travel time and the CO$_2$ emissions at the same time. This “wave” is generally enforced in a more or less static manner. Further to static coordination, we describe in this section how sophisticated applications exploiting mobile opportunistic communications can enhance efficiency, without necessarily introducing high complexity or unbearable implementation cost.

Dynamic traffic light cycle definition
The dynamic adaptation of the traffic light cycles according to traffic conditions has been recognized as a means to achieve the same benefits with the green wave: reduced vehicle stops for shorter travel time and lower CO$_2$ emissions ([20], [21]). This adaptation requires the detection of the traffic conditions which is currently realized through infrastructure-based systems (e.g. cameras, LIDAR systems, etc. as the approach described in [20]) and the communication with the city traffic management authorities for global city traffic management decision making. Mainly due to cost reasons, such a traffic monitoring infrastructure has not been installed in all intersections across cities. Respectively implementations based on wireless communication systems that do not support ad-hoc communications (e.g. as the approach described in [21]) limit scalability, efficiency and cost performance as discussed above.

The same effect in a more efficient manner and capable of handling a wealth of information can be achieved by placing RSUs on the traffic light posts where electric power and Internet connectivity is available, as shown in Figure 3. Cycle adaptation can exploit IEEE 802.11p communication facilities, which allow sensing neighbour nodes within a range. In particular, IEEE 802.11p mandates that OBUs periodically transmit beacon messages including their geographical position and heading (i.e. direction). The IEEE 802.11p protocol stack at the RSU side located on the traffic light post receives the beacon messages from all the vehicles within its reception (or a limited defined by the operator) range. The RSU based on the received beacon messages should be able to detect the lane, side of the crossroad and direction of each vehicle passing by and maintain counters for each direction. An implementation issue that arises in this case affects the trade-off between resource efficiency and speed of execution and the accuracy of location estimation and classification of vehicle to lanes and respective directions of the crossroad. The computation complexity in this case arises from the fact that under different road network topologies vehicles may follow different turns over time frequently changing direction (e.g. complex multi-lane circular road junctions) or vehicles from nearby streets may fall within range of the RSU. Increased accuracy can be achieved by extrapolating the emitted GPS data with GIS data accessible by the RSU. However, this greatly increases processing and memory requirements at the RSU. An equivalent implementation, which can achieve high accuracy at the cost of a slightly higher latency to converge, is to perform concurrent measurements (in many cases assisted by pre-calculated fixed boundary positions) and compute the vehicle direction and decide on the associated traffic flow by statistically processing a number of the latest reported position and heading values. Performing measurement based estimation of the load of each traffic flow based on moving averages light cycle adaptation can be efficiently implemented. Short term statistics and status information can be forwarded to the TCC for processing to perform longer-term estimations, data-base maintenance and status visualization.
The message flow is shown in Figure 4. Statistics collection can be a locally executed application for the dynamic adaptation of the traffic light cycle to the traffic conditions but usually it is expected to reside at the premises of traffic management authorities (state-of-the-art traffic lights already support TCP/IP connectivity for configuration and control) allowing coordination of traffic lights to achieve global traffic control benefits. Beacon messages from OBUs denoted as “MStatus Report” are collected and processed as described above to produce “SStatus Report”. “Event report” messages facilitate the applications discussed in following sections.

**Traffic light as sink for sensed data**

As OBUs are usually equipped with sensors monitoring environmental conditions and the vehicles speed and direction, they are capable of detecting rain (humidity above a certain threshold), ice (a function of humidity and temperature thresholds) or slippery conditions at any location it passes by. With very low complexity, it can store this information in order to transmit it to the first available RSU it will be occasionally find within range. The OBU is capable of discriminating other OBUs from RSUs based on the addressing scheme of the IEEE 802.11p standard with discrete address ranges for different types of devices. Based on this communication scheme, road conditions across all locations can be monitored by traffic management authorities. Subsequently this information can be used to inform drivers and also provide routing advice through VMS or other means. The information gathered at the central application can be visualized using a Graphical User Interface (GUI) as shown in Figure 5. On the left hand side, the available crossroads and
highways can be listed. Choosing among them, the status of the traffic light is shown in real-time along with information about the weather and traffic conditions and a list of detected events reported by vehicles passing by.

![Figure 5: Graphical Representation of the sensed data at the city traffic management center](image)

**Improving safety for pedestrians**

A quite common approach for improving the safety of pedestrians crossing a road is to install a traffic light which becomes red for the vehicles only when a pedestrian indicates its presence by pushing a button on the traffic light post, i.e. the traffic lights provide regularly priority to vehicles. The approach works quite well apart from the case when rain makes it unpleasant both for the pedestrians (to wait until the vehicles stop) and for the drivers (that have to stop on a wet pavement). A lot of times the pedestrians attempt to cross the street running on a wet pavement which may cause severe accidents.

The proposed infrastructure enables the detection of rain and the execution of the reverse logic i.e. regularly providing priority to pedestrians. Rain and special weather conditions in general can be detected either by OBUs or by the RSU (embedding the appropriate sensors). In any case the RSU controlling the traffic light receives and processes weather condition and traffic load information. In case of low traffic, the default vehicle-priority turns to pedestrian-priority state. In this case, green traffic light for vehicles is triggered by the detection of an approaching vehicle or a timer expiration (to ensure a maximum waiting time for vehicles not equipped with OBUs).

**Applications related to highway transportation systems**

The incentives that make citizens willing to pay the associated toll to use a highway (even in presence of alternate routes) include safety and reduced travelling time. These depend on the construction specifications and quality as well as on the measures to prevent primary and secondary accidents. A primary accident can be caused by slippery road or careless driving, while a secondary accident is caused by a primary accident which has not been perceived in time. Secondary accidents are very often equally important (and fatal) as primary ones [23]. In most highways, cameras are installed in regular distances and inspected at the traffic control center by trained staff which reacts to abnormal conditions: a) informing the interested parties (ambulance, fire brigade, police, etc.) and b) defining appropriate messages that should appear in VMSs. This procedure takes significant time compared to the human reaction time and as a result drivers closing fast to an incident may get into danger.

The reduction of the time between the event detection and information dissemination can be reduced based on the C2X communication presented in section 2 where OBUs “automatically” detect abnormal and/or dangerous
situations and disseminate information in the “appropriate” area exploiting either vehicle to vehicle or vehicle to infrastructure communication.

In an example scenario shown in Figure 6, the OBU of a vehicle (say car C) detects a “sudden” change of its speed or slippery road condition. A broadcasted message (event report) then provides the car’s geographical position and the detected event (e.g. slippery road/icy conditions). Assuming that car F is close enough to car C (e.g. their distance is less than 1000m) and moving towards the same direction, the OBU of car F receives the event report directly from car C (over IEEE 802.11p) and a suitable warning (either visual on a display or audio) is triggered. Additionally, events are forwarded backwards within a range to inform all approaching vehicles even out of range to vehicle C and can be announced to the RSU which in turn notifies/warns “interested” vehicles.

Focusing on the implementation aspects, the event detection relies on reading the sensor data and executing simple comparisons with thresholds to decide whether an event that needs further attention/action has been detected, as shown in the pseudo-code describing the application in Figure 7. To avoid fault event detection, the sensors are polled periodically with a period in the range of ms and the event detection is decided and announced only when the comparisons result in the same verdict for a specific number of times.

```plaintext
// Configuration and initialization routines // Neighbor table management
// «beacon» message generation every T_nodeTableMgt sec // HUM & TEMP register update.
if (TEMP<TEMP_C) OR (TEMP<TEMP_M AND HUM>HUM_M) then ICE= TRUE // New Alarm detection and status update
// Alarm Indication inside vehicle
then ICE= TRUE // Alarm reception and forwarding (vehicles within range/direction)
// Alarm table management every T_alarmTableMgt // Alarm table reset
if [RSU Detect] then
EVENT_REPORT message generation
Alarm store
else
Alarm forward /* within range/direction */
// Alarm table management every T_alarmTableMgt
```

Figure 7: Detection logic a) for weather conditions-related event and b) vehicle behavior related events

The definition of the appropriate area for the dissemination of information for abnormal situations (be it relevant to weather or to accidents) is also critical in this case for the effectiveness of the application because information flooding results in neglecting the received information. Especially inexperienced or elderly drivers are sensitive to information overload thus dictating the need to filter the information and pass to them only the information that is relevant. While it seems that the most complex part is this definition and identification of the vehicles that need to be informed, it is the IEEE 802.11p protocol that undertakes this task once the engineer has decided the interested area from a geometrical point of view. Let’s assume that as depicted in Figure 6, the “appropriate” area where the event should be disseminated forms a rectangular with dimensions SxW. Based on
the TSB feature of the Geocast protocol, the device that detects the event can issue a data indication message specifying the center of the rectangular (which is a function of the geographical position of the source and the dimensions S and W of the rectangular), its dimensions (S, W) and its heading. This information is set in the respective GeoAreaPos Latitude, GeoAreaPos Longitude, distance a, distance b and angle fields of the IEEE 802.11p message format respectively. Using the Geocast functionality, both cars B and F will be notified when it enters the interested area, possibly by node B retransmitting the event report message and if the event persists (e.g. ice).

Depending on the detected event and the highway’s dimensions, the “appropriate” area may span both directions of the highway. For example, a weather-related event concerns both directions and thus the rectangle’s W dimension has to double.

Similarly to the case where the RSU attached to the traffic light behaves as a sensed data sink, when an OBU of a vehicle moving in the highway detects an event but at the point of detection no connectivity is achieved, the information related to the detected event is passed to the RSU as soon as the vehicle enters within range, as shown in Figure 8. The RSU communicates this information to the highway operation center as well as to the “interested” drivers, i.e. the drivers in the area that can be defined exploiting the topologically-scoped broadcast feature of the Geocast protocol. The communication with the highway operation center enables wider dissemination of warnings since it a) controls the messages appearing on the VMSs and b) can enforce additional means for the dissemination of information e.g. through mobile phones and radio.

Figure 8: Opportunistic communication is exploited for delivering information to the RSUs

In terms of software and processing requirements the protocol and application implementation is based on the NEC Linkbird Linux operating system accompanied by the NEC C2X-SDK communication system and API, providing geographical routing with advanced features and C based development tools. The C2X-SDK provides access to the 802.11p protocol implementation and interfaces to update and retrieve the necessary data structures including position, speed and direction data and mobile node neighbor database management. The applications described above include polling based -for exchanging regular beacon messages to support the location based 802.11p operation and retrieving sensor data- as well as interrupt based communications -to process asynchronously received messages announcing specific events (Figure 7). Sensed data are retrieved and displayed via serial and USB interfaces developing the appropriate drivers to interface to the peripheral vehicle sensors and display unit and communication with the TCC utilizes a typical client/server model developed over the Linux TCP/IP protocol stack. Thus, the C based applications periodically manage the retrieved information and implement the conditional statements to result to smart decisions regarding announcement of early warning messages and configuration of traffic management parameters like traffic light timing.

**BENEFITS, FACTORS AFFECTING PENETRATION AND FUTURE WORK**
The main benefits of the presented architecture are that it contributes in forming a denser and wider sensing (relay) grid all over the road network. While dynamic traffic lights and dynamic VMS are widely deployed
these days, making them capable of reacting in real-time to detected events all over the road network is expected to significantly improve safety and road experience. The denser the sensing grid is, the more wise and fresh traffic-related decisions can be made, as shown in Figure 9, where the detected events reported from OBUs are listed. On the other hand, the width of the grid directly affects the sensed area and consequently the interested drivers, who can then a) assist in traffic management decision based on global traffic and weather condition knowledge and b) further motivates the purchase of OBUs by citizens. This dense and wide sensing grid comes at almost no cost for the authorities since the only CAPEX involves the purchase of RSUs.

![Figure 9: Example application that lists the detected events on a graphical user interface](image)

The cost of the RSUs but mostly of the OBUs plays an important role on their penetration. The OBU consists of a chipset realizing the IEEE 802.11p protocol, a processor and memory chipset, few attached or embedded sensors and a audio/visual peripheral for communicating with the driver. Apart from the antenna, the rest can be packed on a device with dimensions in the range of few centimeters. Already, prototypes supporting IEEE 802.11p communication can be found commercially available. The development of the applications described in this work are based on the NEC linkbird platform (Figure 10) which comes in a package of 11x14cm providing multiple USB and a serial interface powered by a 64bits MIPS Microprocessor at 266MHz. The NEC linkbird comes with a Linux Operating system (2.6.19 kernel) to provide an open development platform. Reviewing the OBU operations required for the execution of the applications described above, it is evident that the processing load is relatively low and thus a low cost processor is sufficient. As GPS and sensing technology becomes cheaper every day, the cost of such a device for mass production is expected to be well below 40$. The cost could be even lower if this device is combined with devices used for e-toll payment, sharing common packaging and other components. Exploiting the path from the TCC to the RSU and the driver, it is possible to cater routing instructions for the route of interest to each driver, strengthening the incentives for purchasing the OBU. This way the driver can enjoy reduced toll fees and routing instructions apart from safety/weather warnings, all in one. While the estimation of the cost of the device is not at the focus of our investigation, implementing affordable systems and/or system that justify well their cost is mandatory for designing realistic applications.
From the traffic control management perspective, the presented architecture caters abundant sensing information and enables more detailed traffic planning and more sophisticated route guidance. The corresponding decisions and advice can be disseminated to the interested drivers and pedestrians through a variety of communication channels: OBUs, VMS positioned in the highways and in bus stops, and more importantly through mobile phones. Setting up applications that provide routing guidance based not only on geographical information and on historical records of the traffic fluctuations but on real-time traffic and weather conditions has been proven important for both car drivers and bicycle/motorcycle riders as well as for pedestrians. Warning a rider about slippery road and rain can save his/her life exactly as warning a citizen suffering from asthma that CO$_2$ emissions are above a specific threshold. Assuming that a significant part of the citizens are willing to pay for such a service (setting the destination through his mobile phone and receiving back routing guidance and relevant information), the profit can be re-invested in OBU cost sharing to enlarge the sensing grid.

Given that connectivity based on IEEE 802.11p has been tested and provided good results, the next step is to test and evaluate the efficiency of the system at application layer. The latency between event occurrence and information processing at the following cars or the RSU is critical for the efficiency of the system since a vehicle moving at 100km/h speed travels 28m. This time span mainly depends on the sensor sampling interval and processing time in the involved mobile nodes. Having developed the application code as a next step we plan to proceed to instrumented execution and profiling of the source code to identify throughput limitations, latency bounds and potential optimizations. The results of this work are planned to be included in future publications.

**CONCLUSIONS**

In this paper we presented a framework implementing applications targeting road safety and traffic management over mobile opportunistic systems based on the IEEE 802.11p standard. We described the hardware modules and the functional requirements and demonstrated a use case based on the NEC Linkbird-MX hardware platform that provides the IEEE 802.11p communication framework. Having integrated the required hardware peripherals we presented the application logic and identified critical parameters and implementation alternatives that can affect system performance. The applications we described are directly interfaced to the IEEE 802.11p communication stack running on the Linkbird-MX platform and the integrated peripherals supporting sensing and user interfacing. The applications are based on distributed execution of
functional modules implemented on the three main entities that interact in the framework of ITS i.e the OBU, RSUs and TCC. Data aggregation and processing can provide valuable information to drivers and transport infrastructure administration and control authorities for responding appropriately to weather and traffic conditions preventing accidents and proactively controlling and informing the users of the transportation infrastructure enhancing transportation efficiency and safety.

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