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# Benefits of Tight-Coupled Architectures for the Integration of GNSS Receiver and Vanet Transceiver

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**Abstract**—Vehicular ad-hoc networks (VANETs) are one emerging type of networks that will enable a broad range of applications such as public safety, traffic management, traveler information support and entertainment. Whether wireless access may be asynchronous or synchronous (respectively as in the upcoming IEEE 802.11p standard or in some alternative emerging solutions), a synchronization among nodes is required. Moreover, the information on position is needed to let vehicular services work and to correctly forward the messages. As a result, timing and positioning are a strong prerequisite of VANETs. Also the diffusion of enhanced GNSS Navigators paves the way to the integration between GNSS receivers and VANET transceivers. This position paper presents an analysis on potential benefits coming from a tight-coupling between the two: the dissertation is meant to show to what extent Intelligent Transportation System (ITS) services could benefit from the proposed architecture.

## 1. THE ROLE OF TIME AND POSITION IN INTELLIGENT TRANSPORTATION SYSTEMS

A *Vehicular Ad-hoc Network* (VANET) is composed of vehicles, equipped with short range wireless interfaces, which collaborate to form a temporary distributed network enabling communications with other vehicles (or road infrastructure nodes) located in line of sight or even out of the radio range (if a multi-hop network is built among vehicles). Communications can so be grouped into vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) and are aimed at supporting advanced, reliable, fast and secure data delivery for safety as well as non-safety applications.

Safety applications aim at providing drivers with information about critical situations, in order to prevent accidents. In general, the amount of information to be exchanged is relatively small but the applications have strict requirements in terms of transmission reliability, delivery latency and packet dissemination.

Reversely, typical non-safety applications are more bandwidth-demanding. They aim at improving driving comfort and efficiency of transportation systems by offering services such as on-board Internet access, electronic map update, driving through payment.

Safety and non safety applications then pose contrasting requirements on the communication infrastructure that make very challenging the effective design of VANET communication architectures and protocols (such as medium access control, routing, and data forwarding protocols).

Although flooding is the simplest method for broadcasting safety messages, it can lead to well-known undesired effects such as the broadcast storm problem: redundant packet retransmissions result in repeated contentions, collisions, and high latency. The impact of broadcast storms in VANETs, in terms of message delay, packet losses and overheads, is extensively studied, for example in 4.

In general, *emergency message* dissemination in a VANET needs “timely” and “lossless” medium access control (MAC) protocols (*real-time and collision-free delivery*). This is a very demanding requirement: MAC in a VANET needs to be *fully distributed* due to the constantly moving and changing nodes in the network; as an effect of fully-distributed MAC, packets may experience unpredictable delays in media access due to deferrals and back-offs.

On the other hand, VANET characteristics (such as high-speed node mobility, frequent topology change, and short connection lifetime) degrade significantly the performance of conventional topology-based routing protocols designed for Mobile Ad Hoc Networks (MANET). This is due to overhead involved by the control traffic (route discovery, route maintenance, etc.) which is required to perform frequent updates of routing information of the whole network (as well as route failures and transient nature of links).

Summing up, *VANETs set a very challenging context where nodes are expected to work in a completely distributed way* (in order to be flexible and reduce protocol overheads) *but, as an effect, they cannot guarantee*

*deterministic access and scalable routing due to the intrinsic nature of the solution*, which is missing a mutual coordination.

Currently two Standardization Bodies (IEEE and ETSI, respectively in USA and Europe) are mainly making decisions on VANET standards in the 5.9 GHz band. In both cases the emerging solutions (IEEE 802.11p, 1609.0-4 and ETSI EN302571 and TS202663) foresee an amendment to WiFi standard, fitting *Wireless Access in Vehicular Environments* (WAVE) and supporting *Intelligent Transportation Systems* (ITS) applications.

In addition, some recent scientific papers [5, 6, 7] have envisaged the possibility of supporting a distributed synchronous VANET thanks to two different slotted approaches (namely MS-Aloha and STDMA), currently being investigated also in ETSI as a possible next generation solution. For sake of simplicity in the remainder of the paper, the transceiver mounted on vehicles and fixed infrastructure for short-range communications, will be referred to as “WAVE node,” regardless the actual underlying technology.

To complete the picture, the same approaches are being investigated by other Consortia aimed at harmonizing results (Car-to-Car Communication Consortium – C2C-CC, [3]) and at defining a set of interfaces across several media (CALM by ISO). Additional and complementary proposals are coming from other bodies to complete feasibility of end-to-end services (e.g., IETF for routing across VANETs).

All in all, the following trends can be abstracted from standards and scientific literature concerning the role of time in VANETs:

IEEE 802.11p Medium Access Control (MAC) is based on CSMA/CA algorithm which is completely asynchronous and strongly relies on the concept of casual waiting time; the only clock involved in the architecture is a plesiochronous on-board clock.

International literature on VANET has recently revealed a growing interest in synchronous (slotted) MACs, as a last-minute alternative to CSMA/CA, to be investigated for the upcoming international standards.

However, despite the asynchronous MAC, also WAVE includes a synchronous multi-channel access subtending a Control Channel (CCH), which is exclusively to communicate safety and control information, and one or more service channels (SCHs): switching between CCH and SCH is defined according to precise synchronous patterns which require absolute synchronization. As a result, not only in case of slotted MAC but also in case of multichannel CSMA/CA, a strong synchronization is required and an absolute time-source is involved [14] which, as a matter of fact, only GNSS solutions can guarantee.

In addition, a more deducible role concerns the knowledge of position in VANETs. Geographic-routing (also called “*georouting*” or “*geocasting*”) is a routing principle that relies on information of geographic position. It is based on the concept of routing a message exploiting the geographic location of the destination instead of its network address. In VANETs, georouting provides wireless communication among vehicles and among vehicles and fixed stations along the roads: also the geographic position is supposed to be provided by a GPS /GNSS receiver.

Georouting works with a connectionless approach: a stable link to a node or station is not required; moreover it is fully distributed and based on ad hoc network concepts: mobile nodes communicate with each other, and may have intermittent infrastructure access. This approach is well suited for highly mobile network nodes and frequent changes in the network topology.

Accordingly to the nature of the final application, geocasting can support unicast services (when the destination is a specific node, whose position is known), and broadcast services (when the destination is a set of nodes in a certain area). Then the following conclusions can be drawn:

Also positioning is strongly recalled by Vanet communications: georouting exploits information on car positions to improve the routing inside a VANET. It can help both unicasts [8] and broadcast [12] transmissions.

Hence, given the constraints and characteristics of vehicular communications, largely relying on position and time information, and considering the popularity of the satellite system, it is quite natural to imagine the integration of the GNSS receiver and the WAVE transceiver. As a matter of fact such concept is largely mentioned in literature and subtended by all the solutions which are being investigated by car manufacturers [3]. This paper focuses on the architectures which can integrate in most effective and mutually beneficial way the two components inside the so called *On-Board Unit* (OBU).

For this purpose the remainder of the paper is structured in the following way: in section 2 two possible architectures are proposed for OBU: they are analyzed in section 3 evaluating possible respective benefits onto the ITS services currently foreseen in literature; in addition section 3.1 explores some possible novel ITS services which are discussed, showing how they can be enabled only by an enhanced integration between WAVE and GNSS blocks. The discussion is wrapped-up by the final Conclusions.

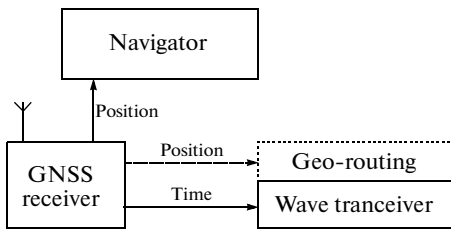


Fig. 1. Loose coupling.

## 2. COUPLING ARCHITECTURES FOR ON-BOARD UNIT (OBU)

While the integration of GNSS and WAVE transceiver has been widely accepted and recognized as a key-enabling point for VANET services, the way such integration should take place has not been standardized. Obviously the most intuitive solution is a straightforward approach where the GNSS receiver constitutes a *pivot* element and feeds both the navigator and the WAVE transceiver with the time-position information required. This introduces the loose coupling (LC-OBU) architecture of Fig. 1.

Such architecture is simple, intuitive and accomplishes all the tasks which are strictly required for a basic operation of the node:

- the position, as computed by GNSS receiver, feeds vehicle navigator;
- the absolute time can easily be tapped for WAVE synchronization;
- prospectively the same architecture can provide position required by georouting algorithms.

While LC implementation can be straightforward, at a deeper analysis, the architecture is too rigid to allow synergies among the sets of information available onboard (to perform the so called *cross-domain optimization*). For this purpose the architecture depicted in Fig. 2 is proposed (TC-OBU – Tight Coupled OBU).

The rationale of TC model can be summarized as follows:

—*Cross-domain optimization* is enabled by a mid-layer which processes heterogeneous data as a whole, optimizing, aggregating and correlating them, providing relevant information as a ready-to-use service towards the basic blocks (e.g., WAVE assistance). Inside the mid-layer engine a data-fusion and data-mining process can be carried-out and a consistency check can be ensured: for instance node position can be the result of not only the absolute positioning coming from the GNSS blocks, but also of data coming from on board sensors (e.g., accelerometers) and from mutual positioning (with the support of WAVE). This way positioning becomes more robust and is acted as a two-way process: information flow takes place first from the tight-coupled heterogeneous blocks up to the mid-layer and than falls back as an aggregated information, from the mid-layer engine down to the heterogeneous blocks.

This is further discussed in section 2.1.

—*Despite the additional logical block (mid-layer), the coupling among blocks becomes tight* because more information can be exchanged among them (not only those of LC). The architecture gains flexibility: e.g., WAVE nodes can share VANET-domain information (road traffic, mutual positioning, maps, ...): all the blocks are likely to improve their flexibility thanks to an enriched information available to them.

—While the integration among technological blocks becomes tight, the navigator becomes an upper block which manages only car routing as well as visualization with a user-friendly and flexible interface. The navigator is then expected to entrust mid-layer with positioning but also to gain a rich set of functions aimed at displaying additional data (traffic, pollution, accidents, ...) and to perform smarter routing (green routing, traffic-aware routing, etc. ...).

—*Additional blocks can be integrated in a quite easy way* (e.g., a block for plate recognition, sensors for

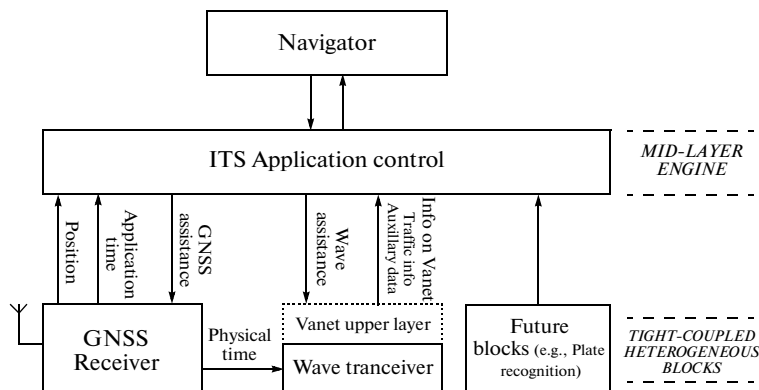


Fig. 2. Proposed tight coupling.

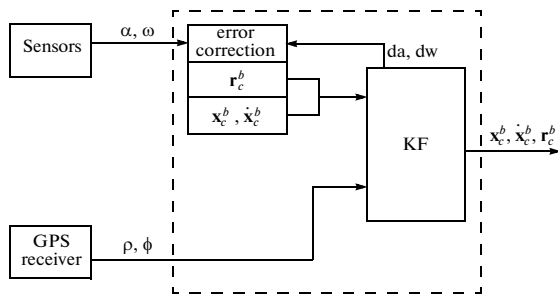


Fig. 3. Closely coupled integration topology.

speed and acceleration, environmental sensors, cameras): either a specific interface is defined for each of them or, in a more flexible way, a standard and scalable bus may be used. In this way the new blocks could be integrated according to a plug-and-play paradigm and would conceptually require little more than a software upgrade, just to manage the drivers of the new devices and to properly process the new information.

—More specifically, concerning the GNSS assistance, the WAVE receiver offers the opportunity to *easily distribute GPS assistance and augmentation information*. For instance EDAS (EGNOS Data Access Service) provides: Raw GPS, GLONASS and EGNOS GEO observations and navigation data collected by the entire network of Ranging and Integrity Monitoring Stations (RIMS) and Navigation Land Earth Stations (NLES); in addition EGNOS augmentation messages, as normally received by users via the EGNOS Geostationary satellites are available via EDAS.

—Finally the tight integration can be reflected also at a very low level, close to the hardware level inside the GNSS receiver (as a feedback loop introduced to drive the GPS receiver). This concept is further discussed in the following subsection and is depicted in Figs. 3–4.

### 2.1 Coupling Architectures at GNSS Receiver Level

So far the issue of the integration between the GNSS receiver and VANET transceiver has been discussed only at an abstract and service-oriented level. However the tight integration between the two logical blocks may have impact also at a lower, level, with direct effects even on the architecture of GNSS receiver itself.

The claimed integration at OBU level corresponds to a specific impact on the architecture deployed at the GNSS receiver. In order to better discuss it, the following description is centered in the case of the integration with INS, however the same ideas can be extended to the case of more complex signals, such those coming from the Mid-Layer Engine depicted in Fig. 2.

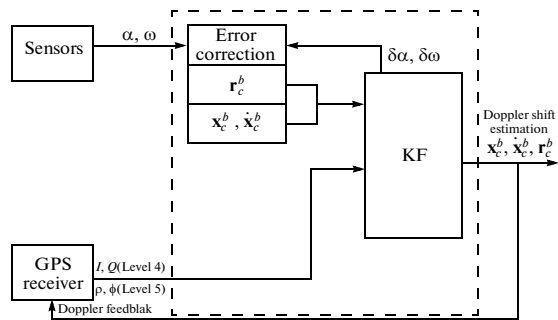


Fig. 4. Tightly and ultra-tightly (or deeply) coupled hybridisation topology.

The advantages and disadvantages of GNSS and INS are complementary. GNSS computations contain relatively high (when compared to short term sensor errors) but upper-bounded errors. Conversely, free inertial navigation is accurate only over short time periods but it drifts over long time periods. Proper fusion of GNSS and inertial navigation solutions can mitigate each system’s errors and take advantage of each system’s strengths, producing positioning performances, which are better than for either type of stand-alone solution. Hence, INS/GNSS integration allows the user to have the benefits of a hybrid solution; maintain a specified level of performance during outages of the GNSS satellite reception; provide a complete six-degree-of-freedom navigation solution ( $X, Y, Z$  translation and rotation) at a higher output rate than is conventionally available from GNSS alone [9]; reduce the random component of errors in the GNSS navigation solution; or provide a GNSS solution in the presence of severe vehicle dynamics and interference.

The simplest solution for INS/GNSS integration is to implement uncoupled hybridization of the different elements. However, state-of-the-art technology considers coupled solutions, with different levels of integration: loose, close, tight and deep or ultra-tight coupling [10].

In the *uncoupled integration*, the independent INS and GNSS solutions are blended together by simple weighted averaging according to the inverse of the covariance matrices predicted in each of the two solutions. As opposed to the uncoupled integration level, in the higher level integration levels, an IMU (Inertial Measurements Unit) dynamic error model must be available; i.e., the model is a stochastic differential equation (SDE) whose unknowns are model parameters that will extend the fundamental (position–velocity–attitude) INS navigation states. These additional unknowns are the so-called calibration states.

In *loose coupling* (LC-GNSSr), the INS processor predicts the (8 or 9) fundamental and the (6 to 24) calibration states with their covariance matrix. The GNSS processor predicts position states. The two sets

of states share, essentially, the position states. The INS/GNSS integration tool—typically, though not necessarily, a Kalman filter—improves the predicted states. The fundamental improved states define the integrated navigation solution and the calibration states are fed back to the INS processor so its next predictions are more accurate than the previous ones. In this way, an eventual GNSS signal outage, would be more easily bridged by the correctly calibrated IMU observables.

In *close coupling* (CC-GNSSr), the GNSS navigation processor disappears and its functions are transferred to the INS/GNSS integration tool that receives the INS fundamental plus calibration states and the GNSS range and/or phase measurements. This adds new states for the receiver clock errors and, eventually, for the carrier phase ambiguities. The integration tool combines (typically in a least-squares adjustment) the predicted INS states (acting as pseudo-observations) and the GNSS measurements. The advantage of close coupling over loose coupling is clear: in loose coupling four or more satellites are required to produce a GNSS measurement (position) while in close coupling each satellite produces a GNSS measurement (range). In other words, in scenarios where too many signals are *weak or absent*, the close coupling approach results in a graceful degradation of the navigation solution whereas the loose coupling approach results in a pure free inertial solution. This integration level is illustrated in Fig. 3.

*Tight coupling* (TC-GNSSr) differs from close coupling in that it adds feedback information to the GNSS receiver. From the known or estimated satellite velocities and receiver's antenna velocities the instantaneous velocities between the various satellites and the receiver's antenna—also called line-of-sight (LOS) velocities—are computed and passed on to the GNSS receiver. The LOS velocities allow the estimation of the Doppler shifts and thus the correct signal reception frequency for the adjustment of the PLL/DLL of the GNSS receiver. This corresponds to the information available from the tight-coupled OBU, hence the same attribute.

Ultra-tight coupling or deep coupling differs from tight coupling in the GNSS observables used in the navigation processor. While tight coupling uses phase and range observables, ultra-tight coupling uses the I and Q observables [11]. The tight coupling and the ultra-tight or deep coupling are illustrated in Fig. 4.

### 3. ITS SERVICES AND OBU ARCHITECTURE

Some recent papers ([15] among them) provide a quite comprehensive list of the applications currently envisaged for VANETs by the main consortia and standardization bodies (ETSI, IEEE, C2C-CC) and studied inside many European research projects (SAFES-POT, CVIS, COME2REACT, SEVECOM). Basically

the services can be grouped into the following three sets: (a) *services for driver assistance* (aimed at increasing safety), (b) *services concerning traffic conditions* (aimed at enhancing efficiency), and (c) *business/entertainment applications*.

**The first category includes all the safety messages** which are expected to decrease the number of fatalities on the roads; among them the following ones can be mentioned: emergency electronic brake lights, slow vehicle warning, intersection collision warning, hazardous location warning, traffic signal violation warning, lane change warning, cooperative forward collision warning and intersection management. Most of the messages are broadcasted (they are announced to all the neighboring nodes, not to a specific destination), are either periodic or event-triggered and typically involve a period and/or a latency of about 100 ms. They may span over one or multiple hops.

Such services are the most important to the stakeholders: they constitute the base-line services and require a simple straightforward implementation since they must be the first to be supported and have higher priority than the others. Coherently with these goals they do not subtend additional and more challenging features (such as routing inside the *Mobile Ad-Hoc Network*—MANET).

As a result they involve very baseline tools and are easily supported also by the simple OBU scheme of loose coupling.

Despite **safety services** may seem to be equally supported by the different architectures, there are however **relevant benefits raised by tight-coupled solutions** (both TC-OBU and TC-GNSSr).

—First of all the positioning can be improved and made faster thanks to TC-OBU (by means of heterogeneous data being processed, assistance and augmentation information carried by WAVE) and to TC-GNSSr (increased precision). This may seem quite obvious but the benefits on the final services can be huge, especially in the case of crowded urban areas where urban canyons and close, parallel lanes are likely to puzzle GNSS receiver: for instance cooperative forward collision warning strongly relies on high accuracy of relative positioning.

—Specific topology-dependant services, such as intersection collision warning and intersection management, may be further enforced by TC-OBU. In the simplest implementation they are built by messages broadcasted by the infrastructure nodes (I2V messages). However if one node approaching to the intersection gets stuck in a jam and is aware of the event thanks to TC-OBU (correlating precise position, speed, number of nodes and other information), it can send additional messages such as the estimated waiting time.

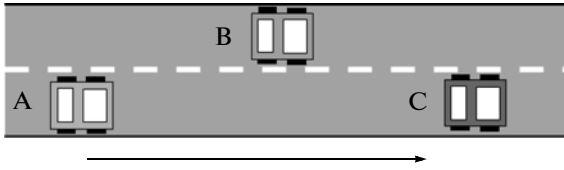


Fig. 5. Non-ambiguous distance.

—As already discussed, the precise and robust timing is a feature strongly improved by TC-GNSSr and critical to WAVE [1]. In fact there is a strong contrast between the use of time by the IEEE 802.11p MAC and WAVE multichannel architecture built on the top of it: while IEEE 802.11p is completely asynchronous (it relies on the concept of casual waiting time and the only clock which is involved in the architecture is a plesiochronous on-board clock). By reverse WAVE requires that multi-channel access over CCH and SCHs is precisely mastered by a common absolute time: synchronization is mandatory and a device must monitor CCH until synchronization is established, in order to transmit. One of the main points of strength of CSMA/CA (the opportunity to work asynchronously) is wiped out by WAVE synchronization requirements [14].

—Safety messages are required a deterministic performance: this is one of the main motivation to the feasibility analysis on slotted and connection-oriented approaches currently being explored inside scientific community and standardization bodies. However slotted approaches such as MS-Aloha [5, 6] can be achieved, once more, only if a precise and stable synchronization is available: in particular a stable synchronization (also when the received signal fades) can be achieved, as already discussed, only with TC-GNSSr (section 2.1).

—Finally it is worth mentioning that there are some emerging solutions which could benefit from TC-OBUs. Among them [12] exploits mutual position

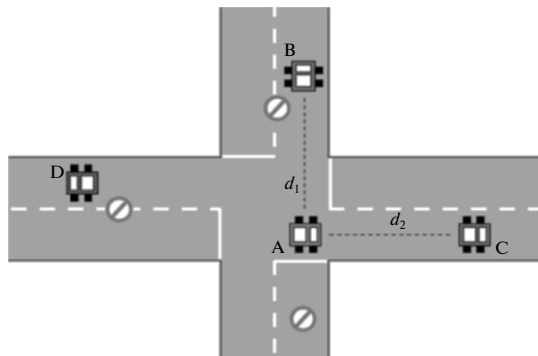


Fig. 7. The concept of Mapcast: only node C forwards A's message, because A is the only in a relevant position for the message.

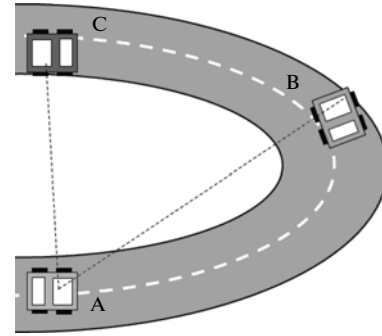


Fig. 6. Ambiguous distance metrics.

to efficiently forward messages over multi-hop paths. These are the main ideas subtended by the solution: if a message has to be forwarded, multiple forwarding by different nodes should be prevented as much as possible to avoid the so called *broadcast storm*; this goal is achieved facilitating forwarding by the farthest nodes receiving the message; from a practical point of view the solution acts on the parameters driving collision avoidance in CSMA/CA (the farther the node, the shorter waiting time). However, as depicted in Fig. 5, the only information on mutual distance can be misleading, while a more context-aware information can let the approach work also with any road shape (such as U-turns). If the road topology is well known also the topology in Fig. 6 can be resolved in a proper way, the node C is identified as farther than B, despite its geometrical distance may be lower.

The same idea has been further extended in a recent paper [13] where the protocol Mapcast has been introduced to make forwarding decision aware of road topology and of message content. More in details the rationale of Mapcast is the optimization of the overall forwarding load by exploiting map information: crossroads, secondary and parallel streets become key concepts in Mapcast and road-topology is tightly integrated in the distributed decision making process. In Mapcast each vehicle runs its own instance of the distributed algorithm: additionally it integrates map information consequently resulting in an enriched and topology-aware decision which is expected to be more efficient (reducing broadcast storms) and more effective (faster and more reliable).

Mapcast extends the same working principles described in [12] while, in addition, the forwarding process is carefully limited to the area of interest: for example, a certain type of message may be relevant to a main street and to the first crossroads and will not propagated in parallel streets. Moreover, since the transmission is circumscribed, the bandwidth is preserved, with benefits especially on safety critical messages.

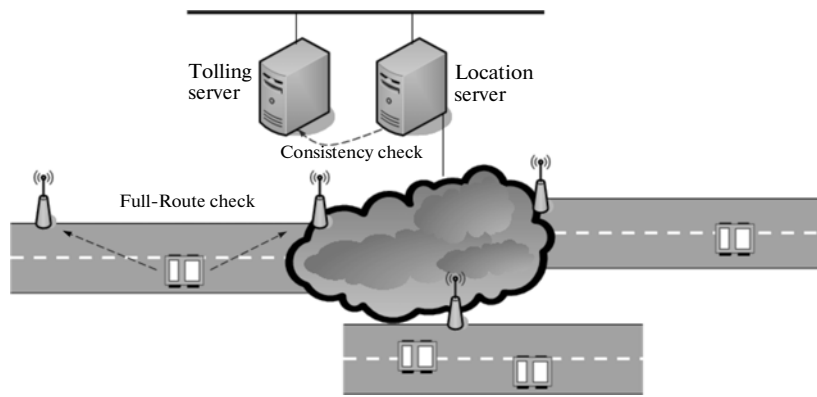


Fig. 8. Robust Tolling by TC-OBUs.

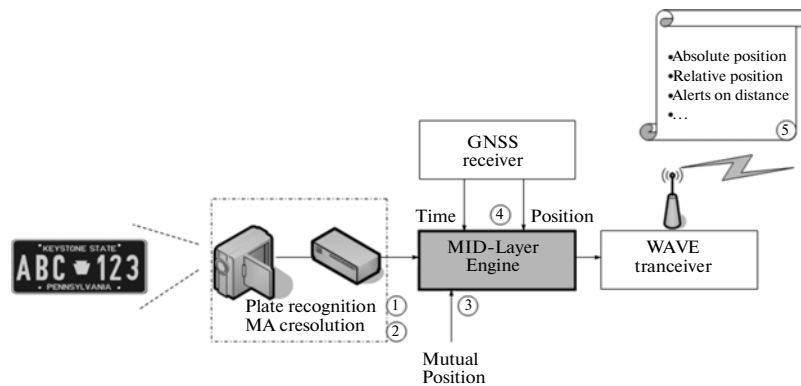


Fig. 9. Plate recognition and unicast alerts.

More explicitly, A node A receiving a broadcast message from S can make decisions based on a refined analysis of position and selecting the proper forwarding criterion: it checks its position in respect to the “source” S and referred to the map (road topology), it considers the kind of message and contemporarily senses the channel in order to verify if any other node has already forwarded the packet.

The second category of VANET services (according to the taxonomy provided in [15]) includes accessory travel-supporting data, such as detour warning, cooperative cruise control and electronic toll. They require a mid priority (lower than safety services) and are supported by messages which are announced at lower rates. Basically all the above services can be easily supported also by LC-OBUs.

However, the TC-OBUs and TC-GNSSr, improve the accessory services in the same way as they do in the case of safety services.

In addition, further benefits may come from TC-OBUs. In particular, a specific role can be played by time-space certification, which can particularly enhance and make more secure and robust the process of payment. Supposing that a logical block devoted to

tolling is among the future blocks indicated in Fig. 2, the financial transaction can be enforced by a mutual authentication involving keys depending also on space and time, which would make identity spoofing harder.

Moreover the overall architecture allows to carry out tolling as a result coming from data collected along the full route (periodically exchanged between each vehicle and the infrastructure and carrying also information on the identity of the vehicles in its neighborhood). Such mechanisms are supposed to counteract possible frauds by the customers against the owner of the infrastructure: multiple checks can be performed along the route of a node A, benefiting also from the information coming from the other nodes (say B, C) about A (Fig. 8). Moreover malicious actions, such as cloning, would be prevented or easily detected.

In other words, the tolling would be only the final action further validating the payment.

The third set of VANET applications (a.k.a additional applications) offer services to passengers and drivers, mostly relying on infrastructure-based communications rather than V2V data exchange. They include Media and Map Download, Remote Diagnosis, Green Routing and can be spread by unicast, broadcast



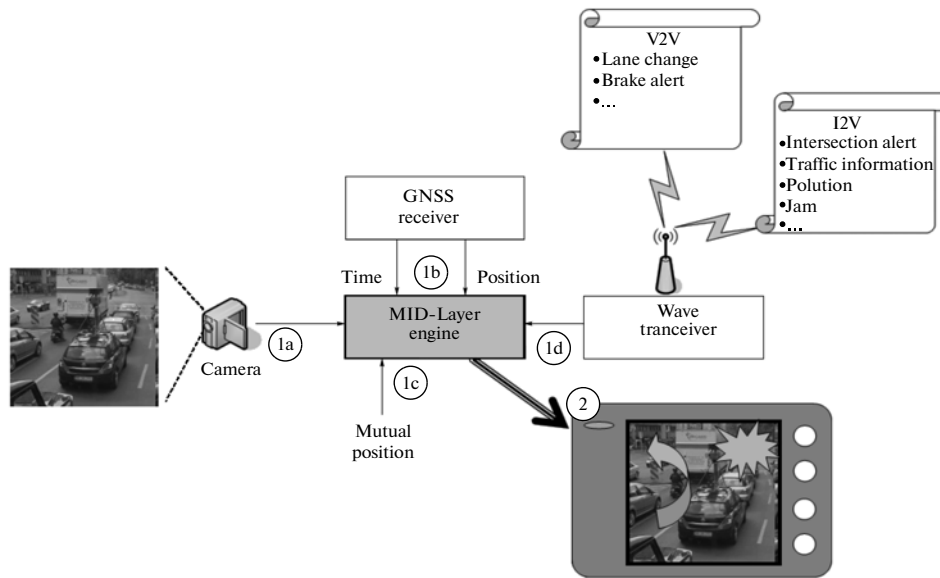


Fig. 10. Enriched Navigation Experience.

or on-demand; most of them are supposed to be mainly unidirectional (download traffic).

Without giving more details, once more the advantages of TC-OBU over LC-OBU—as in the case of safety services, can be reaffirmed.

### 3.1 Possible Novel ITS Services Enabled by Tight-Coupled Obu

In the authors' point of view, the most interesting results concern possible novel services which are enabled only by TC-OBU architectures.

First it is worth recalling that, as already stated, the proposed architecture can grow and foresee additional functional blocks: as a result it is not possible to exhaustively figure out the whole number of novel services. They however represent one strong advantage of TC architecture over LC ones.

For sake of clarity two examples are here below mentioned.

The first example concerns the integration of a plate recognition block inside the TC-OBU and is depicted in Fig. 8. One of the unresolved issues in VANET is the automatic MAC address resolution (the network identifier). Suppose that one vehicle should send an alert message to a specific vehicle, for instance the one which is approaching after and does not respect mutual distance (as required for safe driving). If the alert message were sent in broadcast it would not be effective and would be probably neglected. On the other hand, it is hard to know a priori (or automatically retrieve) the MAC address of the destination.

A possible solution is enabled by the TC-OBU, supposing that the MAC address can be univocally computed by the plate of a vehicle. Effectively plate recognition blocks are already available and can be easily integrated in the TC architecture.

Conceptually plate recognition (1) can feed MAC resolution (2) whose output feeds Mid-Layer Engine. At the same time Mid-Layer Engine can integrate information on mutual position (coming from other on-board sensors (3)) and on absolute position (4). This way vehicle A, preceding node B, can send it a datagram (5) where it specifies: possible alerts, the relative position of B in respect to A and the estimated absolute position of B.

This has also impact on the robustness of positioning of B: the information can be integrated in the GNSS receiver loop according to any architecture model (LC/TC-GNSSr).

All this chain is enabled only by TC-OBU.

From an opposite perspective it is possible to make navigation a more realistic experience, rich in contents. In fact the Mid-Layer Engine can also integrate the heterogeneous information towards the navigation block: for instance it can merge the 3D information coming from the on board stored map (thanks to the position (1b)) with the visual information (1a) coming from on-board cameras (e.g., front and rear cameras) and the traffic, accidents, jam, pollution information coming from the WAVE block (1d) and other sensors (1c).

This scenario well motivates the original idea of making the Navigator an upper layer, collecting the

integrated information, as generated by the mid-layer engine.

As depicted in Fig. 10, the mid-layer engine provides the end-user interface with a rich set of integrated information which could not be (coherently and efficiently) managed without a TC-OBU architecture.

The navigator can now show not only maps and directions, but also events, alerts and real views.

#### 4. CONCLUSIONS

The paper has presented possible alternative architectures aimed at integrating GNSS and WAVE blocks inside the OBU of future vehicles. The solutions span from a loosely to a tightly coupled integration model which is applied both in a cross domain context and at the pure GNSS layer.

This way the LC-OBU, TC-OBU, LC-GNSS<sub>r</sub>, and TC-GNSS<sub>r</sub> have been defined and analyzed regarding their efficiency and flexibility in supporting VANET services.

Attention has been paid both to services currently foreseen within international Consortia and Standardization Bodies and to those which have not been explored yet.

The analysis has highlighted that, despite the more complex architectures, the TC solutions offer more integrated functionalities which have positive effects on the robustness of the state-of-the-art services and enable new ones, which cannot otherwise be supported.

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