A Traffic Monitoring and Queue Detection System Based on an Acoustic Sensor Network

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***Abstract*—Wireless Sensor Networks for real time traffic monitoring in Intelligent Transportation Systems is currently considered one of the challenging application area for this emerging technology. The promise of an unmanaged infrastructure, with a continuously decreasing cost per unit, attracts the attention of both final users and system integrator, opening new business opportunities. This paper describes a Traffic Monitoring Wireless Sensor Network system, based on acoustic arrays and powered by an effective post-processing detection. A practical case study is presented starting from a real problem and reaching the best architectural solution with particular focus on hardware implementation and communication protocol design. Finally, real experience results are shown to highlight the reliability of the developed system.**

***Keywords*-wireless sensor network; acoustic sensors; traffic monitoring; cross-layer routing protocol.**

I. Introduction

Real-time traffic monitoring and early queue detection is of paramount importance in Intelligent Transportation Systems (ITS). Distributed traffic monitoring on a large scale based on non intrusive/obtrusive solutions are highly desirable for traffic monitoring.

Conventional traffic surveillance systems make use of intrusive sensors such as inductive loop detectors or pressure sensors, for high accuracy in vehicle detection. However, these sensors disrupt traffic during installation and repair, and therefore have high installation and maintenance costs. These limitations have pushed towards the development of non-intrusive traffic monitoring technologies, including laser radars, passive infrareds, ultrasonics, passive acoustic arrays and video cameras. These systems have high equipment costs and their accuracy depends on environmental conditions. Moreover video cameras have involved huge data volume demands for a dedicated wired connection in order to communicate with the central server. As a result these solutions are not suitable for large-scale deployment and hence are restricted to small scale applications, where isolated monitoring points are located many kilometers apart.

Passive acoustic transducer-based surveillance systems have also been developed, featuring vehicle classification and multi-lane resolution capability; this is based on processing the characteristic sounds emitted by vehicles [3] [4]. Acoustic sensors are attractive especially for their low cost and simple and non-intrusive installation, however they require a sophisticated post-processing algorithm for extracting useful information.

Another relevant requirement pushing towards the design of an effective traffic monitoring system is to provide high spatial density measurements. A viable solution for achieving that purpose is a system based on a Wireless Sensor Network (WSN) infrastructure offering advantages in terms of flexibility and a significant reduction of installation costs; therefore making large scale deployment possible.

Several solutions based on wireless sensors have been investigated, including wireless magnetic sensors [5] [6], and coherent cross-correlated acoustic transducer [8]. Ding et al. [5] demonstrated wireless magnetic sensors embedded in the road sampling the magnetic field at its front and back ends, and internally processing this data in order to count vehicles for computing the average speed of passing vehicles.

The requirements that adopting a WSN are expected to satisfy in effective traffic monitoring monitoring concern both system level issues (i.e., unattended operation, maximum network life time, adaptability or even self-reconfigurability of functionalities and protocols) and final user needs (i.e., communication reliability and robustness, user friendly, versatile and powerful graphical user interfaces). The most relevant mainly concerns the supply of stand-alone operations. To this end, the system must be able to run unattended for a long period also in the absence of electricity. This calls for an optimal energy management ensuring that the energy spent is directly related to the amount of traffic handled and not to the overall working time.

An additional requirement is robust operative conditions, which needs fault management, since a node may fail for several reasons. Other important properties are scalability and adaptability of the network's topology, in terms of the number of nodes and their density in unexpected events with a higher degree of responsiveness and reconfigurability. Finally, several user-oriented attributes, including fairness, latency, throughput and enhanced data querying schemes [10] need to be taken into account even if they could be considered secondary with respect to our application purposes because the WSN's cost/performance trade-off.

In this paper, a WSN based on an array of acoustic sensors that detect and process the sound waves generated by the traffic flow using a low-cost microprocessor is proposed.

The paper is organized as follows: Section II provides an outlook on the system's composition and operation. Section III and Section IV describe the hardware and the basic operation of each constitutive element. Section V discusses the communication protocol. Finally, Section VI gives the experimental results of a continuous long-term operation.

II. TM-WSN DESCRIPTION

This paper describes a novel traffic monitoring (TM) system based on a Wireless Sensor Network (WSN) infrastructure; the TM-WSN system allows traffic monitoring and queue detection to be performed in real-time at an unprecedented space scale with an extremely low investment in installation and maintenance costs.

A significant characteristic of the system is the WSN infrastructure that combines, in its *basic module*, two kinds of nodes which are both based on *acoustic sensors*, yet they employ different operation techniques and hence, have different hardware characteristics.

The basic module of the system is composed of a Master Node (MN), which has superior computational and energy resources and is connected to a remote database via TCP/IP over UMTS. The MN is wirelessly connected to a number of regularly spaced Sensor Nodes (SNs) operating on a low duty-cycle and woken-up on demand. A basic module infrastructure deployed along the motorway is shown in Figure 1 . This module can be spatially replicated on both sides of the motorway to cover a wide area.

The sound signal is detected and processed by the embedded resource of the MN using an original algorithm that allow to automatically extract *traffic parameters* on site. The information is transmitted to a central server and made available to a remote user.

When a queue or traffic jam is detected at the MN location the SNs are activated by the MN in order to locate the position of the queue or traffic jam, thus providing a real-time picture of the traffic flow sampled at the same space interval as the SN deployed on the motorway. The communication between the devices is performed by a cross-layer MAC Routing protocol which will be described in Section V.

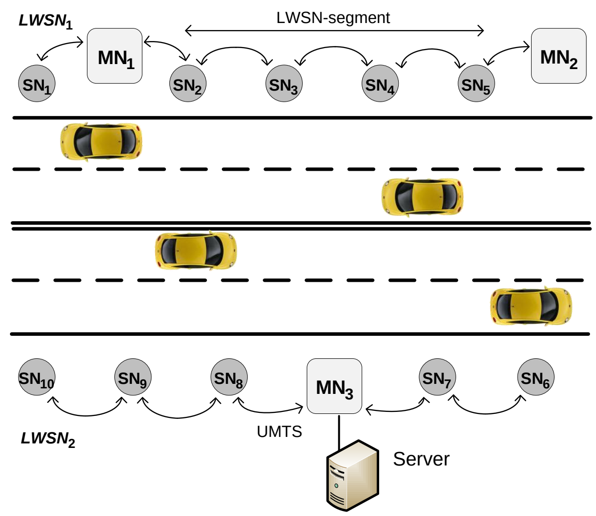


Figure 1. Basic system infrastucture.

III. MN DESIGN AND OPERATION

In this section is first illustrated the MN hardware solution adopted and then, the procedure allowing automatic extraction on-site of traffic parameters.

A. MN Hardware Design

The MN block diagram is shown in Figure 2. It is composed of a Sensor Unit which detects the audio signal coming from the road and a Computational Unit which performs the signal processing and vehicle detection while it simultaneously supports communication with both the associated SNs by the RF Unit and with the central server by the UMTS modem.

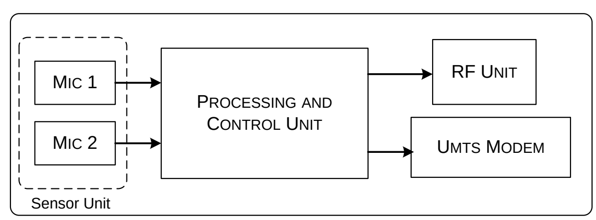


Figure 2. MN hardware block diagrams.

The computational unit consists of a commercial computer on module GUMSTIX VERDEX PRO XM-4 with a Marvell PXA270 400 MHz processor equipped with 64 MB RAM and 16 MB flash memory, and operating with a Linux OS. The audio signals detected by the acoustic sensors are sampled at 16 KHz and quantized at 16 bit, then processed with a real-time algorithm based on FFT routines for estimating the time delay via a coherent cross-correlation method.

A TCP-IP over UMTS Modem provides a bidirectional connectivity to the central server thus enabling a remote control of the MN operative parameters and creating an upgrade of the systems. The RF unit is based on Texas Instrument CC1000 low power transceiver operating in the UHF ISM band, implementing an FSK Manchester coding.

The setup of the MN is packaged into a compact lightweight panel which can be easy installed on the motorway's guardrail.

B. MN Operation and Parameters Extraction Procedure

All vehicles emit characteristic sounds when moving on the road. The sound signal is connected to the source's position therefore, in reference to [4] [8] traffic sensing and vehicle detection can be achieved by processing the signal detected by the acoustic sensor.

The *sensor unit* consists in a pair of microphones (MIC1 and MIC2) arranged in a characteristic setup and deployed along the roadside, with the baseline parallel to the moving direction of the source, as shown in Figure 3.

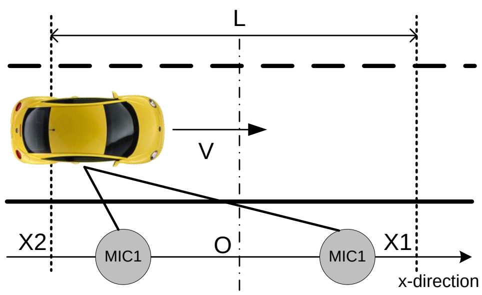


Figure 3. MN sensor unit setup.

The sound wave generated by a passing vehicle reaches the two microphones at slightly different times due to the difference in the air path; on the two signals a *cross-correlation method* is applied to estimate the time delay according to [4] [7].

The signal detected by the MIC1 and the MIC2 are respectively:

$$s_1(t) = s(t) \quad (1)$$

and

$$s_2(t) = s(t - \Delta t) \quad (2)$$

where $s(t)$ is the sound wave generated by the source (vehicle) and Δt represents the time delay between the two signals arriving at the two microphones.

The cross-correlation function of the two signals, $R_{12}(\tau)$ is formulated by:

$$R_{12}(\tau) = s_1 * s_2(\tau) = s * s(\tau - \Delta t) = R(\tau - \Delta t) \quad (3)$$

where $*$ denotes the convolution and $R(\tau)$ the auto-correlation function of $s(t)$.

According to [9], the signal produced by vehicles is a broad band, random-noise signal providing a cross-correlation function with a distinct peak at $|t - \Delta t|$.

In the cross-correlation domain, the position of the peak represents the source's time delay and changes with its position. Mapping the position of the peak in a time interval results in a digital *Sound Map*, which represents the source motion along a predefined track. A typical sound map is shown in Figure 4(a); the x-axis represents the observation time and the y-axis represents the time delay τ.

If further traveling speed is assumed as constant, the detected sound trace could be described by an analytic solution, accordingly with [], and could derive from the sound path difference in the air and expressed by:

$$\tau(t) = \frac{1}{V_s}\left[\sqrt{\left(x+\frac{d}{2}\right)^2 + y_0^2 + z_0^2} - \sqrt{\left(x-\frac{d}{2}\right)^2 + y_0^2 + z_0^2}\right] \quad (4)$$

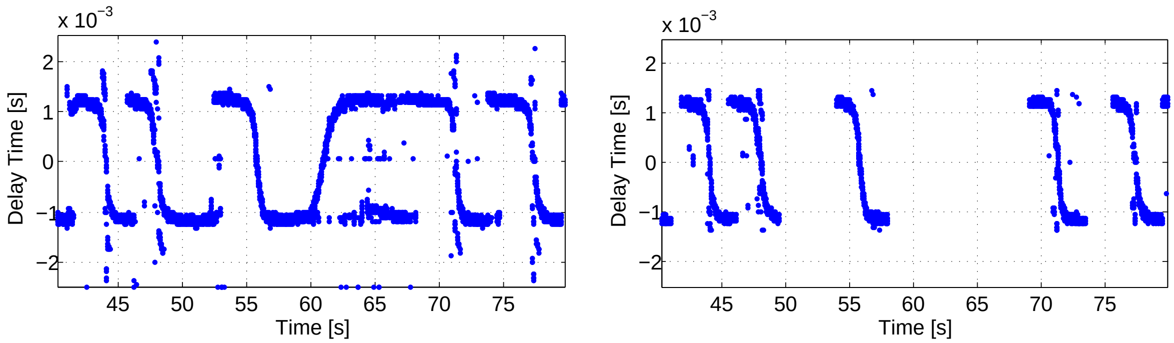
where, V_s is the speed of the sound in air, d is the microphones spacing, x is the vehicle position in the x-direction, y_0 is the distance between mics and vehicle, z_0 is the height of the mics above the ground.

Owing to the linearity of the cross-correlation, *multiple sound sources* can be processed, and thus they could appear in the Sound Map. Unwanted sound sources derive from background noises, typical of each complex outdoor environment, and vehicles moving in the opposite carriageway. As Figure 4(a) shows, the vehicles in the Sound Map appear as traces with an opposite slope whereas background noises appear as isolated points.

To enable an automatic reading of the map in an embedded environment, it is necessary to develop an effective post-processing algorithm. For that purpose very clear sound maps are required, where unwanted traces and surrender noises are both removed. Therefore a "cleaning" procedure has been implemented during the making of the sound map. As the energy associated with vehicles traveling in the opposite carriageway suffers from attenuation due to propagation effects, the related correlation peaks exhibit a much lower amplitude with respect to those coming from the nearest carriageway. Therefore a dynamic threshold, estimated on the average energy value, is applied at the front-end of the process. Furthermore, a reduction of the background noise has been attained, by limiting the time delay range of the correlation peak, consistently with the set up geometry.

As result of the procedure described, a Sound Map is given in Figure 4(b) and can be compared with the sound map shown in Figure 4(a). An automatic traffic parameters extraction can now be performed.

A Sound Map corresponding to a single vehicle transit is shown in Figure 5. We can observe that when the vehicle crosses the orthogonal axis of the setup, corresponding to the point "O" in Figure 3, the time difference is zero.



(a) Sound Map.

(b) Sound Map after the post-processing.

Figure 4. Sound Map before and after the post-processing.

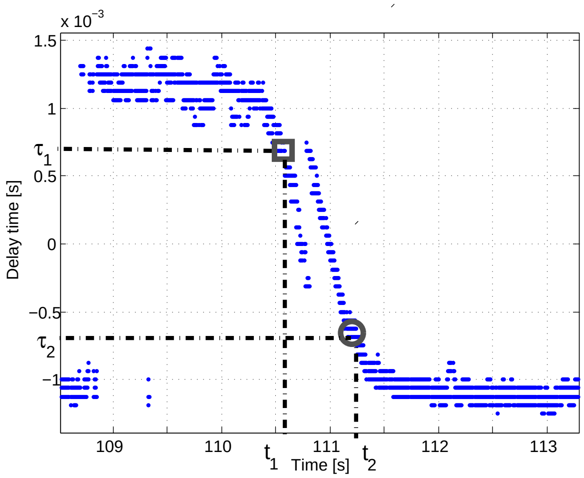


Figure 5. Vehicle detection.

As demonstrated in [8], the trace slope in this point is proportional to the vehicle speed.

As mentioned before, multiple sound sources could appear in the sound map. As in a vehicle the main acoustic source is represented by vehicle tyres; each sound map for a single vehicle, would consist of a two or more traces, each corresponding to a vehicle axle. This phenomenon can be observed in Figure 5.

To detect a *vehicle transit*, two symmetrical points corresponding to the positive time delay τ_1 and the negative time delay $\tau_2 = -\tau_1$ are positioned on the y-axis of the Sound Map (see Figure 5). Those time delays correspond to two symmetrical position, X1 and X2, of the vehicle along the traveling path, whose spacing is L (see Figure 3 for reference). A vehicle transit is detected if the sound trace intercepts the values τ_1 and τ_2 in a sequence that occurs when a vehicle pass through the two virtual positions X1 and X2. Therefore as τ_1 and τ_2 are selected in the linear portion of the trace, the vehicle traveling speed, V_v, can be easy calculated, according to the following expression:

$$V_v = \frac{L * k}{t_2 - t_1} \quad (5)$$

where k is a scale factor taking into account the vehicle axle tracks, D_{axle}, and $t_2 - t_1$ is the time interval taken by the vehicle to cover the distance L, as shown in Figure 5. The scale factor k is used to compensate the asymmetrical behavior of a generic vehicle trace, due to the above mentioned fact that there are two sound sources in the vehicle's front and back axle. Accordingly k is expressed by $L + D_{axle}/L$ and was estimated on a statistical basis. The resulting approximation in estimating vehicle traveling speed is consistent in our case, however, the system aims at evaluating the average traffic parameters, rather than the vehicle parameters. Square and circle markers in Figure 5, thus, represent the sequence associated with the transit of a vehicle, while the vehicle speed is evaluated according to (5).

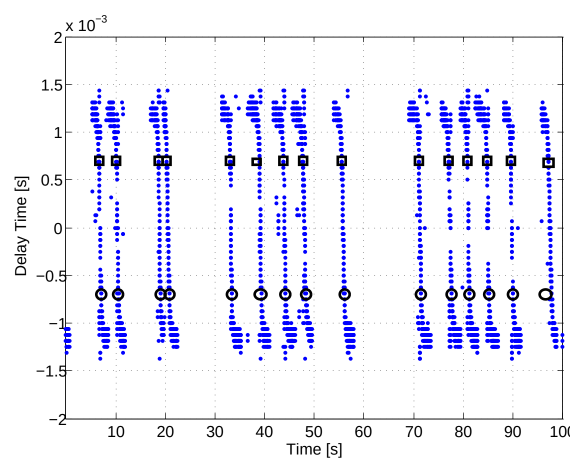


Figure 6. Multiple detection transit.

In Figure 6, a Sound Map is reported, showing the sequence of square and circle markers associated to multiple vehicle detection obtained from the previously described automatic procedure. As it can be observed all the passing vehicles are successfully detected in this case.

The output of the traffic parameters extraction routines is represented by some traffic parameters which indicate the traffic conditions at the MN location. These parameters are included in a summary report and sent to the central server.

The previously described method for traffic parameter extraction was extensively tested during a long period of continuous operation. In Section VI, we present the results of the long-term system operation.

IV. SN Design and Operation

In this section is illustrated the hardware design of the SN along with the SN operation.

A. SN Hardware Design

According to the proposed architecture, the sensor network also includes SN with limited computational capability, only relying on autonomous energy resources. The block diagram of the SNs is represented in Figure 7.

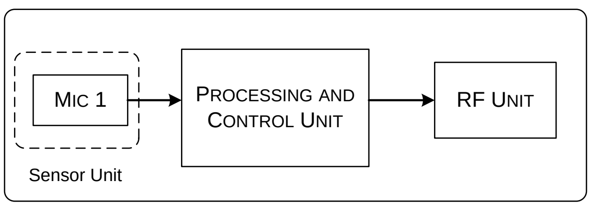


Figure 7. SN hardware block.

The main components of a SN are: the Sensor Unit, which consists of a single microphone, the Processing Unit ARM CORTEX M3 72 MHz, the RF Unit which has a Texas Instrument CC1000 low power transceiver operating in the UHF ISM band, implementing an FSK Manchester code.

The SN primary energy source consists of a 3 V Li-Ion rechargeable battery assisted by a 5 W solar panel as a secondary source. To preserve the battery life, the SNs are duty-cycled at an appropriate low rate.

B. SN Operation and Queue Detection Algorithm

As previously mentioned, the main job of the SNs is to produce traffic reports on-demand for dynamically locating the position of a queue or traffic jam. When a traffic queue or jam is detected at the MN location, the SNs associated with the MN are switched to *operative mode*, the detection of traffic conditions (fluid flow or queue) is performed through an analysis of the energy distribution features. As long as the SNs stay in the operative mode, they regularly produce a traffic report containing traffic conditions information that is passed to the MN according to a scheduling time interval. Communication between the devices is performed by a cross-layer MAC Routing protocol as described in Section V.

The MN reports the information to the central server about the traffic conditions at each individual SN; as a consequence, the *traffic flow distribution* is sampled at the same spacing interval as the SNs deployed on the motorway, thus a complete real-time picture of traffic flow is provided to the user/customer.

The SNs are able to estimate the acoustic energy generated by the traffic. The acoustic signal sensed by the microphone is first high-pass filtered at 1 KHz to cut-off background and wind noise components present in the environment. High-pass filtering is also useful to remove unwanted low-frequency contributions generated by vehicles traveling in the opposite carriageway, for instance, the sound generated by the air-stream of trucks; high frequency (above 1 KHz) energy components, mainly generated by the tyre noise of vehicles traveling in the opposite carriageway, are greatly attenuated by propagation effects. The energy detected by the SN is dominated by the sound sources in the nearer carriageway result in a well defined and space-limited acoustic footprint.

In Figure 8, an energy distribution associated with a traffic flow is presented. In the left side is a distinct peak corresponding to a *passing vehicle*; in the center of the trace a smoother energy distribution can be observed, representing the *standing vehicles*.

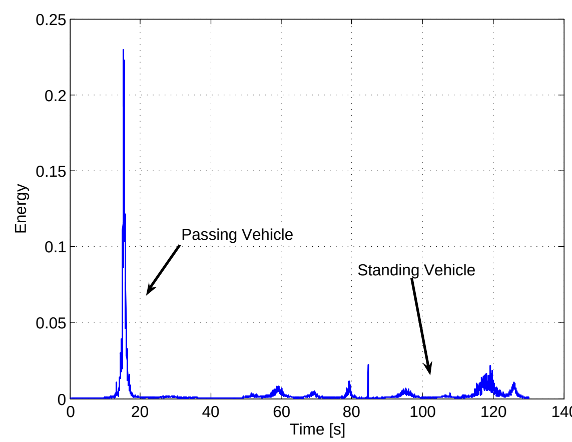


Figure 8. Energy distribution.

In fact, at vehicle speed in excess to some 30 Km/h, the dominant acoustic energy source is represented by *tyres*, featuring well defined energy peaks in the time domain; for standing vehicles, however, the dominant acoustic energy source is represented by *motor noise*, featuring a smoother energy distribution, with a much lower associated energy average. The conditions of regular traffic flow and queues/traffic jams in the nearer carriageway can be classified accordingly.

In fact, a fluid traffic condition is associated to the presence of isolated energy peaks, whereas a queue or traffic jam condition is associated to an energy floor, with a much lower associated energy average.

The processing unit computes the energy distribution in the time domain and an algorithm based on a state machine detects the passing vehicle. An adaptive threshold estimated on the energy value's moving average is on the basis of the state machine. A block diagram of the processing is shown in Figure 9.

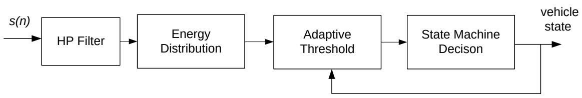


Figure 9. Block diagram of SN operation.

Figure 10 shows the result of this process compared with the sound map generated by the MN. It can be seen that in this case the implemented algorithm is capable of detecting all the peaks in the energy's distribution, as the vehicles are spaced a good distance apart. In heavier traffic conditions, however, the vehicle counting could be underestimated but, in any case, the energy distribution represents a useful indicator for estimating the traffic flow in the carriageway.

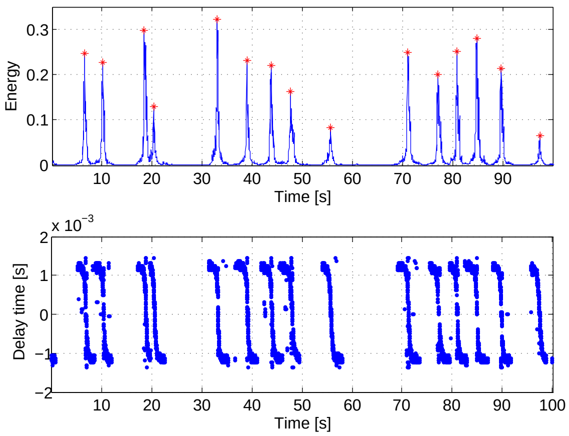


Figure 10. Correlation between energy distribution and sound map.

V. Protocol Design

The most relevant system requirements, which lead in the design of an efficient Medium Access Control (MAC) and Routing protocol for WSNs, mainly concern power consumption issues and the possibility of a quick set-up and end-to-end communication infrastructure. This calls for optimal energy management since a limited resources and node failure may compromise WSN connectivity. Therefore, the MAC and the network layer must be perfected ensuring that the energy used is directly related to the amount of handled traffic and not to the overall working time.

Other important properties are the *scalability* and *adaptability* of network topology, in terms of number of nodes and their density. As a matter of fact, some nodes may either be turned off or may join the network afterward.

Taking these requirements into account, a MAC protocol and a multi-hop routing protocol were implemented. A multi-hop approach was preferred as opposed to a star topology because it also helps to realize an end-to-end communication in the presence of obstacles (i.e., flyovers, trees, curves) that would otherwise prevent the establishment of a direct link between the SNs and the MNs.

Let us start our analysis by considering the wireless network architecture shown in Figure 1. It is comprised of two opposite Line Wireless Sensor Networks (LWSNs) deployed opposite each other (i.e., along the opposite carriageway of a motorway). Each LWSN is composed by at least one MN and a variable number of SNs. Let a *segment* be an array of regularly spaced adjacent SNs of the same LWSN. Each segment is associated with one or at most two MNs, the right and the left one.

The proposed MAC and routing protocol are described and the performance are presented in the following sections.

A. MAC Layer Protocol

The proposed MAC protocol is characterized by the state diagram shown in Figure 11(a).

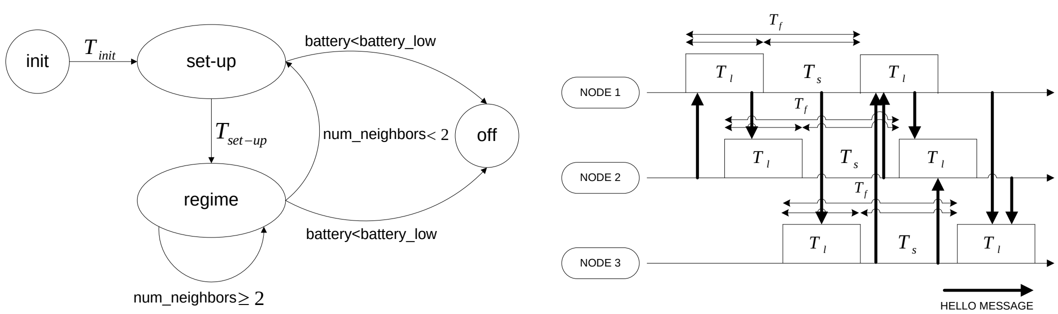
According to it, each node (master/sensor node) wakes up independently, entering an initial idle state (*init state*) in which it remains for the time interval necessary for performing the elementary CPU operations and to be completely switched on (T_{init}). Moreover, before entering the set-up state, each node starts to organize the time into frames whose durations are T_f.

In the *set-up state* each node tries to identify its neighbors and to establish a time synchronization with them. To this purpose it remains in a *listening mode* for a time interval equal to $T_{set-up} \geq 2T_f$ and begins to periodically broadcast a HELLO message sending its *ID* and its *phase*. The phase is the time interval after which the sender exits from the set-up state and enters the regime state. A node that receives a HELLO message adds the source node to the list of its own active neighbors and transmits an acknowledgement.

Once the set-up state has expired, each node enters the regime state. Within this state the operation mode is duty cycled with a periodic alternation of listening and sleeping sub-periods whose time intervals are T_l and T_s respectively. The duty cycle function is given by the following formula:

$$d = \frac{T_l}{T_f} = \frac{T_l}{T_l + T_s} \quad (6)$$

In the *regime state* each node is updated and tries to preserve the synchronization with its neighbors. To this purpose, as Figure 11(b) shows, it sends a frame-by-frame HELLO message in a unicast way to the active nodes in its list according to the phase transmitted by them in previous HELLO messages. As in the set-up state, the HELLO



(a) Finite state machine description of the proposed MAC protocol, involving the transitions occurring among *init*, *set-up*, *regime* and *off* states.

(b) MAC protocol HELLO messages exchange.

Figure 11. MAC protocol description

message contains the *ID* and the *phase* that, in this case, is the time interval after which the sender claims to be again in the listening status waiting for the HELLO message. The phase ϕ is evaluated according to the following rule:

$$\phi_1 = \tau - T_l \quad (7)$$

if the node is in the sleeping mode, where τ is the time remaining to the beginning of the next frame. Conversely, if the node is in the listening status, ϕ is computed as:

$$\phi_2 = \tau + T_s \quad (8)$$

The channel access is managed using the Carrier Sense Multiple Access with the Collision Avoidance (CSMA/CA) scheme, as specified in [11]. This mechanism is very effective in reducing collisions, while the problem of hidden nodes [12] is still partially unsolved.

Each node remains in the regime state until there are at least two neighbors, otherwise it reenters the set-up state in search of connectivity.

To complete the protocol characterization, whenever a node battery is depleted, this node turns off entering the *off state*.

In order to fully characterize the proposed MAC approach, the energy cost per frame interval of a single node (master/sensor node) can be evaluated as follows:

$$C = c_{rx} d T_f + c_{sleep}[T_f(1-d) - NT_{pkt}] + NC_{tx} \quad [mAs] \quad (9)$$

where c_{sleep} and c_{rx} represent the sleeping and the receiving costs $[mA]$ and C_{tx} is the single packet transmission costs $[mAs]$, T_{pkt} is the HELLO packet time length [s] and finally N is the number of neighbors.

In Figure 12, the energy cost per frame interval is shown of each single node as a function of the number of its neighbors. The considered parameters, summarized in Table I, are those relative to the real hardware platform. Moreover, in Figure 12 the accuracy of (9) is highlighted: the analytical results are similar to those obtained with the simulation model developed through the network protocol simulator *NePSing* [14].

Table I
DATA SHEET PARAMETERS OF THE CONSIDERED HARDWARE PLATFORM

Parameter	Symbol	Value
Frame interval	T_f	30 s
Listening interval	T_l	500 ms
Duty cycle	d	1.6 %
Sleeping cost	c_{sleep}	100 μA
Receiving cost	c_{rx}	25 mA
Packet transmission cost	C_{tx}	0.148 mAs

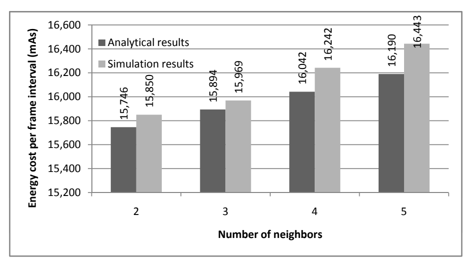


Figure 12. Single node energy cost per frame interval

Finally the protocol is compared with S-MAC and Wise MAC in terms of current consumption as the number of neighbour nodes changes. The Figure 13 highlights the computed performance.

B. Routing Layer Protocol

In order to evaluate the capability of the proposed MAC scheme in establishing effective end-to-end communications within each LWSN, a routing protocol was introduced and integrated according to the *cross layer* design principle [13]. Periodical information is sent which is needed for building and maintaining the local routing tables depicted in Table II.

It resorts to the signaling introduced by the MAC layer with the aim of minimizing the overhead and making the system more adaptable in a cross layer fashion. In particular,

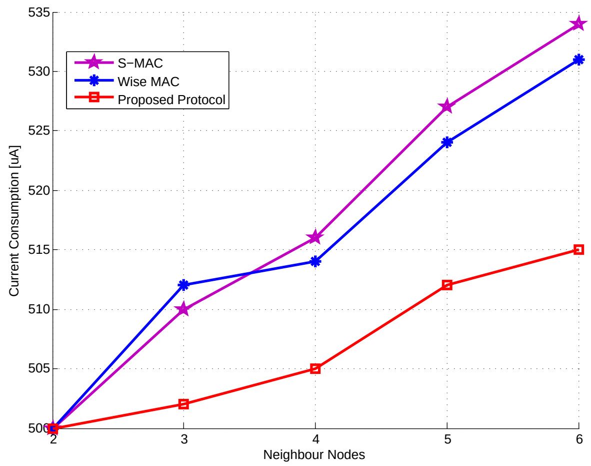


Figure 13. Current Consumption vs. Neighbour Nodes

Table II
ROUTING TABLE GENERAL STRUCTURE

Master Node	Next Hop	Hop Count	Loop Flag
MN_1	SN_1	η_A	false
MN_1	SN_2	η_B	true
MN_2	SN_3	η_C	true

the parameters transmitted along a MAC HELLO message, with period T_f, are the following:

- *ID destination*. If the sender node is in the set-up state, the ID destination will be the broadcast one; otherwise, it will be the ID of the receiver node.
- *ID source*. The ID source is the ID of the sender node.
- *phase*. If the sender node is in the set-up state, the phase will be the time interval after which the sender node exits from the set-up state and enters the regime state; otherwise, it will be the schedule time at which the sender node enters in listening mode according to (7) and (8).
- $ID\ MN_1$. If the sender node is a SN, the $ID\ MN_1$ will be the ID of the first MN which the SN is associated with; otherwise if the sender node is a MN, it will be set at 0.
- *Next Hop 1 (NH_1)*. If the sender node is a SN, the NH_1 will be the ID of the next hop neighbor used by the SN to reach the MN_1 with the minimum number of hops; otherwise if the sender node is a MN, it will be set at 0.
- *Hop Count 1 (HC_1)*. If the sender is a SN, the HC_1 will be the distance from the MN_1 in terms of minimum number of needed hop; otherwise if the sender node is a MN, it will be set at 0.
- $ID\ MN_2$. If the sender node is a SN, the $ID\ MN_2$ will be the ID of second MN which the SN is associated with; otherwise if the sender node is a MN, it will be set at 0.
- *Next Hop 2 (NH_2)*. If the sender node is a SN, the NH_2 will be the ID of the next hop neighbor used by the SN to reach the MN_2 with the minimum number of hops; otherwise if the sender node is a MN, it will be set at 0.
- *Hop Count 2 (HC_2)*. If the sender is a SN, the HC_2 will be the distance from the MN_2 in terms of minimum number of needed hop; otherwise if the sender node is a MN, it will be set at 0.

In the *init state*, each SN sets NH_1 and NH_2 at 0 and HC_1 and HC_2 at a high value chosen a priori.

In the *set-up state*, each LWNS begins to self-organize. Starting from the MNs, the routing information is flooded through the network by each SN.

The routing table is filled up or updated by each node according to the following rules.

As an SN receives a HELLO message from an MN it is associated with, it inserts a row in its routing table (or updates an existing one) assigning the ID source to the "Master Node" and the "Next Hop" fields, a value equal to 1 to the "Hop Count" field and the false value to the "Loop Flag" field.

As an SN receives a HELLO message from an SN belonging to the same segment.

1) it inserts a row in its routing table (or updates an existing one) assigning $ID\ MN_1$ to the "Master Node" field, the ID source to the "Next Hop" field and HC_1 to the "Count Hop" field;
2) if NH_1 parameter contains its own ID, it will assign the true value to the "Loop Flag" field; otherwise it increments by 1 the "Hop Count" field and assigns the false value to the "Loop Flag" field.

The same procedure is ran for the $ID\ MN_2$, NH_2 and HC_2 parameters.

As an SN receives a HELLO message from an SN belonging to an adjacent segment, it discards the information.

As an MN receives a HELLO message from an SN belonging to the left or the right segment, it discards the information concerning itself and stores the other ones in its routing table.

As a node receives a HELLO message from a node belonging to the opposite LWSN, it stores the information in its routing table without any control or preprocessing.

Finally, in the *regime state* each node updates its routing table frame by frame thanks to the reception of HELLO messages from its neighbors. A node deletes an active neighbor from its routing table if it does not receive any acknowledgment for three consecutive frames after the transmission of HELLO messages.

Figure 14 graphically shows the procedure described above for a simple LWSN composed by one segment. In this example it is suppose that each node communicates only with the two adjacent nodes. Let us consider the node labeled SN_1. During the first frame it receives two HELLO messages, one from MN_1 and the other from SN_2 (see Figure 15). Then it updates its routing table. Only the first row contains useful information. According to the network topology taken into the account, SN_1 has to wait the second frame to complete its routing table and know the next hop to reach the MN_2. During the third frame a loop is verified.

From MN1

ID dest	ID source	phase	ID MN1	NH1	HC1	ID MN2	NH2	HC2
0	MN1	5	0	0	0	0	0	0

From SN2

ID dest	ID source	phase	ID MN1	NH1	HC1	ID MN2	NH2	HC2
0	SN2	2	MN1	SN2	infty	MN2	SN2	infty

Figure 15. HELLO messages sent by MN_1 and SN_2 during the first frame

Once the routing table has been filled, each node may derive the proper metric depending on the type of the application message that it has to manage. The application messages are subdivided into two categories: *query messages*, sent by the MNs to query the SNs, and *response messages*, sent by the SNs in response to a query message. If an SN has to send a response message, it will select from its routing table the next hop neighbor that has the "Master Node" field equal to the ID of the destination MN, the minimum "Hop Count" value and the "Loop Flag" field set at false. Then it forwards the message to it. This procedure is performed by every SN received. If an SN receives a query message sent by an MN it is associated with, it will send the message to every neighbor that belongs to the same segment and has the "Master Node" field equal to the ID of the sender MN, the "Loop Flag" set to true and the "Hop Count" value higher than its own MN distance value.

A *recovery state* is introduced to provide a fault-tolerant communication. If an SN does not find any neighbor of the same segment for establishing an end-to-end communication with one of the MNs it is associated with, it will send a HELP message to all the active neighbors of the opposite LWSN. Therefore they look for an alternative path to reach the involved MN, trying to establish a link with a node located in the same segment of the calling-for-help node.

VI. Experimental Results

A prototype, composed of a basic unit of the system has been deployed near Florence, along the A11 highway operated by Autostrade per l'Italia SpA (ASPI) in order to obtain on-field testing and evaluation (Figure 16). The system has been placed closely to a loop detector to test the MN functionality.

The MN unit was first deployed on May 2009; since then it has undergone extensive operation, regularly collecting and transmitting traffic flow reports for the central server at a 60 second rate. Various data typologies were collected by the system to monitor the traffic flow, jams or queues. Some results are provided in the following figures.

Figure 16. Prototype system photograph.

In Figure 17, a weekly data collection of vehicle transit and average speeds is shown, highlighting the periodicity of the traffic flow with different behavior depending on the day and hours. The MN yield is validated by the comparison with the loop detector (Figure 18). As it is shown, the two systems have collected the same results in terms of shape and vehicle transit; only slightly differences can be evaluated comparing the two graph. During the night, in fact, there is an overestimation of the vehicle transit due to a preliminary setup of the system related to the noise floor site.

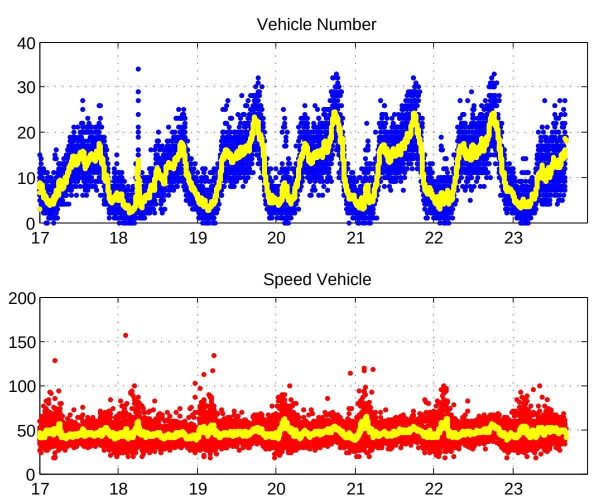
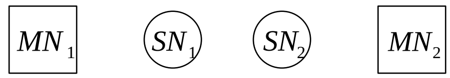


Figure 17. Vehicle transit and average speed for a weekly observation slot.

As a consequence, the MN information is now fully integrated into the ASPI information system; Figure VI



1st frame

SN1 ROUTING TABLE

Master Node	Next Hop	Hop Count	Loop Flag
MN1	MN1	1	false
MN1	SN2	infty	false
MN2	SN2	infty	false

SN2 ROUTING TABLE

Master Node	Next Hop	Hop Count	Loop Flag
MN2	MN2	1	false
MN2	SN1	infty	false
MN1	SN1	infty	false

MN1 ROUTING TABLE

Master Node	Next Hop	Hop Count	Loop Flag
MN2	SN1	infty	false

MN2 ROUTING TABLE

Master Node	Next Hop	Hop Count	Loop Flag
MN1	SN2	infty	false

2nd frame

SN1 ROUTING TABLE

Master Node	Next Hop	Hop Count	Loop Flag
MN1	MN1	1	false
MN1	SN2	infty	false
MN2	SN2	2	false

SN2 ROUTING TABLE

Master Node	Next Hop	Hop Count	Loop Flag
MN2	MN2	1	false
MN2	SN1	infty	false
MN1	SN1	2	false

MN1 ROUTING TABLE

Master Node	Next Hop	Hop Count	Loop Flag
MN2	SN1	infty	false

MN2 ROUTING TABLE

Master Node	Next Hop	Hop Count	Loop Flag
MN1	SN2	infty	false

3rd frame

SN1 ROUTING TABLE

Master Node	Next Hop	Hop Count	Loop Flag
MN1	MN1	1	false
MN1	SN2	2	true
MN2	SN2	2	false

SN2 ROUTING TABLE

Master Node	Next Hop	Hop Count	Loop Flag
MN2	MN2	1	false
MN2	SN1	2	true
MN1	SN1	2	false

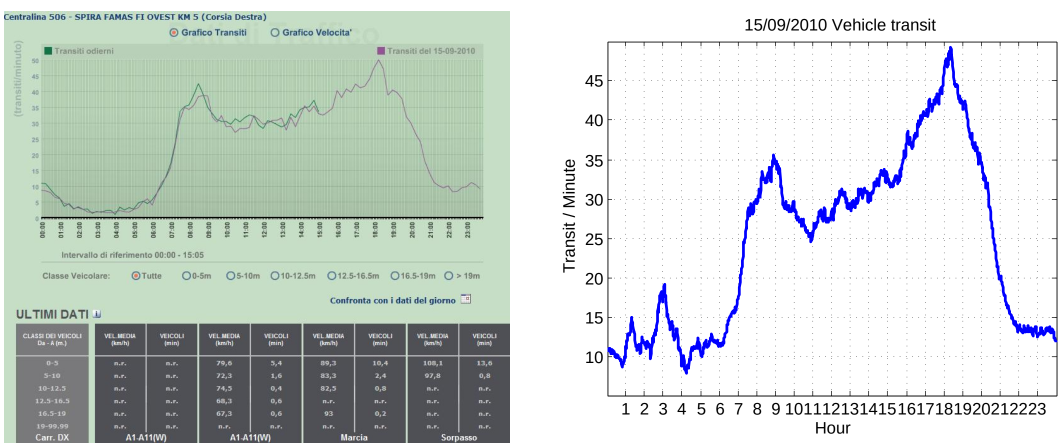
MN1 ROUTING TABLE

Master Node	Next Hop	Hop Count	Loop Flag
MN2	SN1	3	false

MN2 ROUTING TABLE

Master Node	Next Hop	Hop Count	Loop Flag
MN1	SN2	3	false

Figure 14. Example of Routing Tables



(a) Loop Detector.

(b) Audio System.

Figure 18. Comparison between audio sensor and loop detector results.

shows the ASPI public user interface where information from various sensors typologies are available. In particular, a summary report obtained by the MN is presented. Currently the ASPI interface is not able to present SN reports in graphic format; this work is still in progress.

Extensive tests during the period of operation have provided the motorway practitioners with a complete report on traffic trends. Due to the yield and easy deployment of the system, a 50 km, dual carriageway complete installation is planned by ASPI to fully exploit the potential of the system in the A1 motorway, between Florence and Arezzo.

VII. Conclusion

In this paper, a novel sensor network architecture and communication protocol for traffic surveillance has been proposed, exhibiting the unique feature of providing a complete and immediate traffic flow status in real-time at an unprecedented scale. The main features are low installation

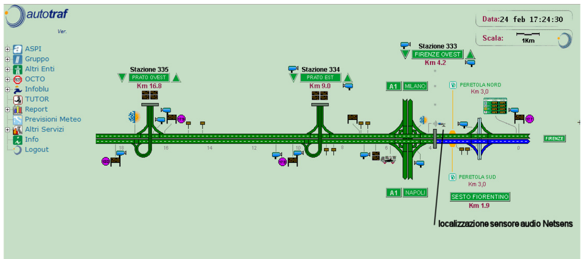


Figure 19. ASPI user interface.

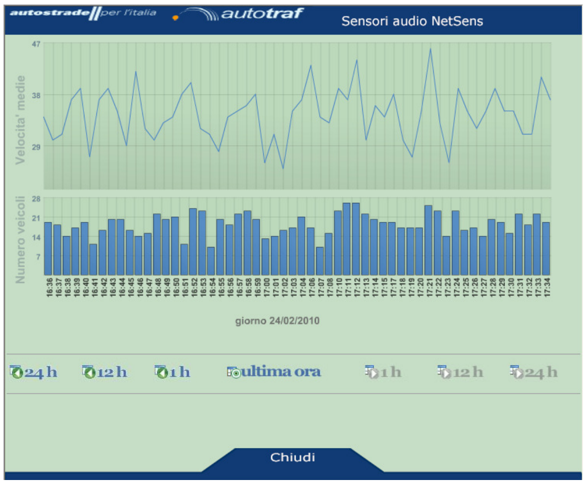


Figure 20. Daily report.

and maintenance costs due to the sensing elements based on the use of passive acoustic transducers. Experimental results, coming from long-term testing performed on a motorway, have demonstrated the effectiveness and yielding of the approach for providing traffic authorities with detailed information about traffic parameters. Thanks to the promising results obtained by the pilot site, ASPI has approved an extensive system installation along the A1 motorway.

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