Acoustic Sensor Network for Vehicle Traffic Monitoring

Barbara Barbagli, Gianfranco Manes, Rodolfo Facchini
Department of Electronics and Telecommunications, University of Florence
Via di Santa Marta 3, 50139 Florence, Italy,
Email: barbara.barbagli@gmail.com, gianfranco.manes@unifi.it
rfacch@gmail.com

Antonio Manes
Netsens S.r.l.
Via Tevere 70, 50019 Florence, Italy
Email: antonio.manes@netsens.it

***Abstract*—Real time traffic monitoring is a fundamental requirement for improving the efficiency of transportation systems. The emerging technology of wireless sensor networks (WSNs) allows of distributed traffic monitoring systems at large scale with low cost of installation and maintenance. The develop of cheap sensor nodes with integrated computing and wireless communication capabilities has changed the scenery of real-time traffic data acquisition. This paper describes a WSN based on an array of acoustic sensor employing an effective signal processing and a novel parameter estimation procedure. Key features are traffic monitoring and localization of traffic congestion event performed in real time, with an impressive space scale. A particular case study is presented starting from a real problem and achieving the best architectural solution. Finally the results of theoretical analysis and extensive experimental results of a prototype installation on a motorway are provided.**

Keywords - wireless sensor networks; traffic monitoring system; acoustic sensors; vehicle detection; traffic parameters estimation.

I. Introduction

Traffic monitoring and vehicle detection is of paramount importance in Intelligent Transportation Systems (ITS). Improving the efficiency of transportation systems has tremendously economical and environmental impact. Traffic management systems, to address the task of an effective management road strategies, require accurate estimation of traffic parameters such as average vehicle speed, density, percentage of occupancy lane. A desirable traffic monitoring system should (i) allows a large-scale deployment, (ii) be passive and operate at low power, (iii) operate in all weather day-night conditions, and (iv) be cheap and easy to install and maintain.

System design must include the choice of a particular sensor as well as the development of adequate signal processing and parameters estimation method.

Many alternatives exist for collecting data about the transit of road vehicles at a given location. Traffic sensors commercially available at present can be divided into two groups, intrusive and non-intrusive sensors, based on their placement. Sensor placement has significant effects on the cost of installation and maintenance, quality of sensing, lifetime of sensors, and disruption of traffic.

Intrusive sensors include inductive loops, magnetometers, microloop probes, pneumatic road tubes, piezoelectric cables, and other weigh-in-motion sensors. They are installed directly on the pavement surface. The main advantage of these sensors is their high accuracy for vehicle detection. However, they have some drawbacks especially the high cost due to the disruption of traffic during installation or repair. As a results, those solutions are not suitable for large-scale deployment and hence are restricted to small scale applications.

These limitations have pushed towards the development of non-intrusive traffic monitoring technologies, including radar, infrared, or ultrasound based detectors; video cameras and microphones. Like the former sensors, the latter could detect vehicle's transit and also they could provide vehicle speed, vehicle classification, and lane coverage. On the other hand, they are expensive, power-hungry and may be affected by different environmental conditions.

The acoustic sensors are attractive especially for the low cost for unit and the simple and non intrusive installation, but at the same time they require sophisticated post-processing algorithm to extract useful information. The problem of detecting vehicles with passive acoustic transducer has been addressed in many studies. Mainly, two approach have been developed: with a single transducer or with an array of microphones. In particular Lo and Ferguson [5] have formulated a nonlinear least-squares method to estimate the motion parameters of a target with broadband acoustic energy spectrum. Valcarce et al. [4] have proposed a maximum likelihood estimate for vehicle speed detection. Forren and Jaarsma [2] have detected vehicles by exploiting the tire noise, using signal correlations among three known microphones under assumption that vehicle has signal with a stationary characteristic. However, they do not model any interference effects of the tires.

Another relevant requirement pushing for the design of an effective traffic monitoring system is to provide a high spatial density measurements. A viable solution for achieving that purpose consists of a system based on a Wireless Sensor Network (WSN) infrastructure which reduces the required investment, enables the employment in large-scale and allows future developments of systems based on multiple sensors that collaborate in collecting informations. Several wireless sensor networks have been investigated, including wireless magnetic sensors [3] [6], and acoustic vehicle detection based on coherent cross-correlation [8].

In this paper, we propose a Wireless Sensor Network that utilizes a microphone array to detect the sound waves generated by the road vehicles. System nodes process sound signals locally to extract traffic parameters on site rather than transmitting the measurements, in order to save both in energy and in bandwidth. The basic principle of the sensing technique is to measure the temporal variation of the differential time of arrival of the acoustic signal at each pair of sensors with an algorithm based on a generalized cross-correlation method. The collected information are transmitted to a central server and made available to a remote user. In comparison with existing traffic sensors, the proposed system offers lower installation and maintenance costs, is less intrusive to environment and allows the detection of traffic congestion location.

In particular, the paper is organized as follow. An outlook of the system composition and operation is presented in Section II. Section III and Section IV describes the hardware and the basic operation of System nodes. Section V briefly present the communication protocol. Finally, in Section VI, experimental results of continuous long term operation are shown.

II. System Description

Vehicle detection and traffic monitoring is an important and demanding application of WSN. The equipment and maintenance cost and time-consuming installations of existing sensing systems prevent large-scale deployment of real-time traffic monitoring and control. This leads to deployment of traffic sensors only at critical location which work independently of each other. Small wireless sensors with integrated sensing, computing, and wireless communication capabilities offer tremendous advantages in low cost and easy installation.

We propose a real-time traffic monitoring system based on a WSN infrastructure, the system allows traffic monitoring and queue detection to be performed in real-time at a larger space scale with an comparably low investment in installation and maintenance costs. The developed system is composed of two different sensor nodes having different hardware characteristics and employing different sensing techniques. The sensors work together in collecting traffic information in order to obtain an excellent spatial resolution and allow to detect the location of a traffic congestion condition (traffic jam or queue).

In Fig. 1, a basic module infrastructure deployed along the motorway is represented. This module can be spatially replicated on both side of the motorway to coverage a wide area.

The basic module of the system infrastructure 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 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.

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. 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.

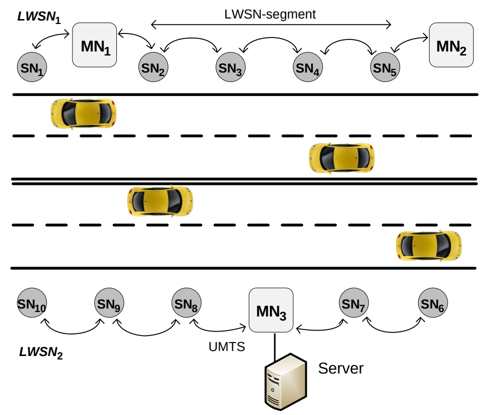


Fig. 1. Basic system infrastructure.

III. MN Design and Operation

Each Master Node is composed of a Sensor Unit detecting the audio signal coming from the sound sources and a Computational Unit which performs signal processing and vehicle detection while supporting at the same time the communication with both the associated SNs by the RF Unit and with the central server by the UMTS modem. The setup of the MN is packaged into a compact lightweight panel which can be easy installed at motorway's guardrail.

A. Sound Map

Figure 2 shows the arrangement of the *sensor unit*, consisting in a pair of microphones (MIC1 and MIC2), separated by $2b$ m and installed with the baseline parallel to the road. We suppose that vehicles travel on a straight path along the road, at the distance of D m, with a constant speed v_0 over the time period of interest. The time observation windows is $\left[-\frac{T}{2}\frac{T}{2}\right]$.

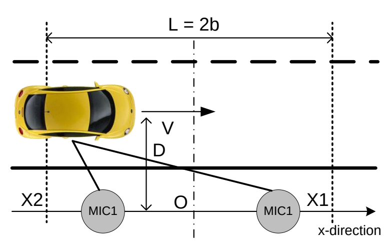


Fig. 2. MN Sensor unit setup.

Sound signals generated by traveling vehicles reach the two microphones at slightly different times due to the difference in the air path; the propagation time delay is $\tau_i = d_1\left(t; v_0\right)/c$

where c is the speed of sound in air. The two received signals can be expressed as:

$s_1(t) = s(t)$ and $s_2(t) = s(t - \tau)$

The issue of estimating the vehicle's speed can be reduced to a Time Delay Estimation (TDE) problem. The objective of TDE is to determine the relative time difference of arrival (TDOA) between signals received by a different sensor. The generalized cross-correlation (GCC) method is the most popular to do so and is well explained in an paper by Knapp and Carter [7].

The cross-correlation of the two signals function yields:

$$R_{s_1 s_2}(t) = \int s_1(t)s_2(t)(t-\tau)d\tau = s_1(t) * s_2(t) \quad (1)$$

where $*$ is the convolution operation.

The cross-correlation $R_{s_1 s_2}(t)$ obtain is maximum when $t = \tau$. So the differential time, between the two signals, can be acquired by get the maximum of the cross-correlation function.

The calculation of the cross-correlation could be done in the Fourier transform domain, thus in the digital processing it could be implemented with the FFT to reduce the computational workload. The Fourier transform of the equation is:

$$F\left[R_{s_1 s_2}(t)\right] = F\left[s_1(t) * s_2(t)\right] = S_1(f) * S_2^*(f) \quad (2)$$

Therefore, the calculation of the cross-correlation will be transformed to a Fourier transform, a multiplication and a Reverse Fourier transform of the two signals $s_1(t)$ $s_2(t)$.

In the cross-correlation domain, the position of the peak represents the time delay, and changes with the position of the source. Measuring the temporal variation of the time delay, corresponding with the position of the cross-correlation peak, in a certain observation time interval; we can create a digital Sound Map, representing the source motion along a predefined track.

A typical sound map is shown in Fig. 3; the x-axis represents the observation time and the y-axis represents the time delay τ.

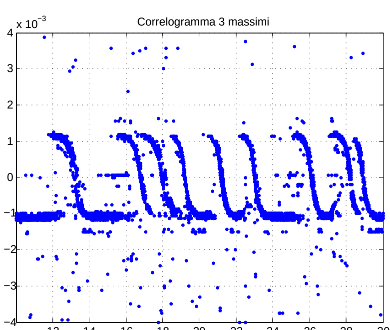


Fig. 3. Sound Map.

A vehicle passing in front of the sensor unit leaves a recognizable trace that could be described by an analytic solution, according to [8]. The shape of the curve could be derived from the sound path difference in the air and expressed by:

$$\tau(t) = \frac{1}{c}\left[\sqrt{(x+b)^2+y^2+z^2} - \sqrt{(x-b)^2+y^2+z^2}\right] \quad (3)$$

where, c is the speed of the sound in air, d is the microphones spacing, $x = v_0 t$ is the vehicle position in the x-direction, $y = D$ is the distance between mics and vehicle, z is the height of the mics above the ground.

The problem for acoustic sensor vehicle detection is to achieve robust vehicle detection under various acoustic noise corruption, as can be observed in the sound map. Since the sensor nodes are powered by battery the solution has to be a low power demanding the development of an efficient algorithm. To achieve that goal, a solution based on a filtering band-pass and a phase correlation method has been adopted. The band pass filter is designed to remove the unwanted background acoustic and the noise, whose spectral contributions where found in the frequency domain below 500HZ.

The *phase correlation* is a GCC method, in which the transform coefficients are normalized to unit magnitude prior to computing correlation in the frequency domain. Thus, the correlation is based only on phase information and is insensitive to changes in sound intensity. Although experience has shown this approach to be successful, it has the drawback that all transform components are weighted equally, whereas one might expect that insignificant components should be given less weight.

A Sound Map after the described processing is shown in Fig. 4; if it is compared with the one of Fig. 3, a relevant improvement in the term of sharpness could be observed. An automatic traffic parameters extraction procedure, from this map, can now be developed.

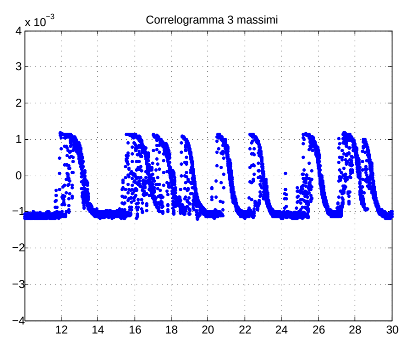


Fig. 4. Sound Map after the post-processing.

B. Parameters Extraction Procedure

In Fig. 5, a Sound Map corresponding to a single vehicle transit is reported. Multiple sound source could be processed and hence 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 two or more traces, each corresponding to a vehicle axle.

With the reference of Fig. 2, it could be observed that when the vehicle crosses the center of the setup, corresponding

ISBN: 978-1-61208-241-7

to the point ”O” or CPA (Closest Point of arrival) the time difference for the two signals is zero. This correspond with the crossing of the x-axis in the sound map, in the neighborhood of this point the curve can be approximated, with a straight line, and hence could be demonstrated that the trace slope is proportional to the vehicle speed.

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 Fig. 5). Those time delays correspond to two symmetrical positions, X1 and X2, of the vehicle along the traveling path, whose spacing is L (see Fig. 2 for reference).

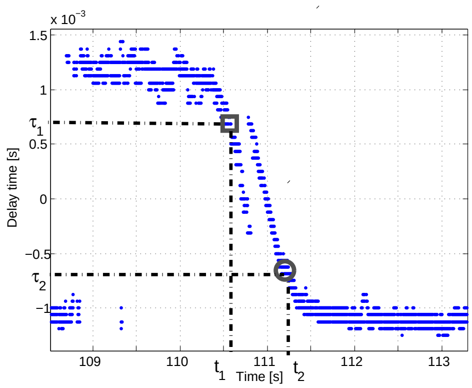


Fig. 5. Vehicle detection procedure.

A vehicle transit is detected if the sound trace intercepts in sequence the values τ_1 and τ_2 that occurs when a vehicle passes through the two virtual position 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:

$$V_v = \frac{Lk}{t_2 - t_1} \tag{4}$$

where *k* is a scale factor and was estimated on a statistical basis.

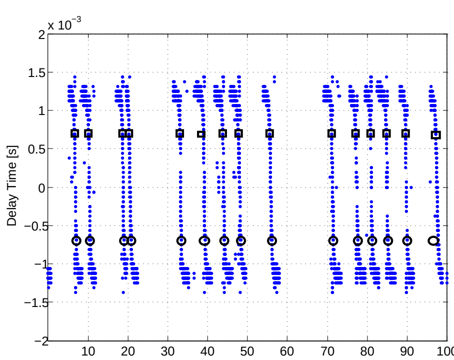


Fig. 6. Multiple detection transit.

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

The output extraction routines are represented by some parameters indicating the traffic condition at the MN location. These parameters are related in a summary report and sent to a central server.

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

IV. SN Design and Operation

According to the proposed architecture, the sensor network also includes Sensor Nodes. 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 detection of traffic conditions (fluid flow or queue) is performed via analysis of the energy distribution features. With reference of Fig. 7, the energy distribution of the acoustic signal associated with the traffic flow could be observed. Moving vehicles yield well defined energy peaks in the time domain, instead, standing vehicles, feature a smoother energy distribution and exhibit a much lower associated average energy.

Thus a qualitative information of a *fluid traffic* condition, is associated to the presence of isolated energy peaks, while a *queue* or *jam* condition is associated to an energy floor, with a much lower associated average energy.

The processing unit computes the energy distribution in the time domain and an algorithm based on a state machine detects the passing vehicle. According to[3], 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 8.

The acoustic signal sensed by the microphone is first high-pass filtered to remove the contribution of background noise and opposite roadway vehicles noise. Due to this signal conditioning the energy revealed by the sensor is mainly associated to the vehicles traveling in the close carriageway.

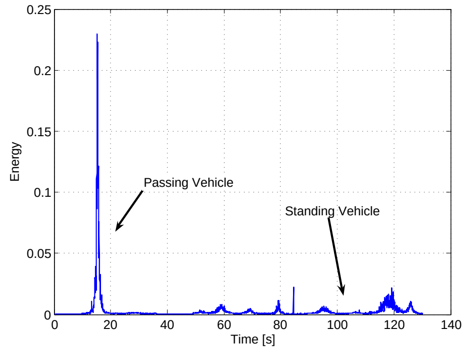


Fig. 7. Energy distribution.

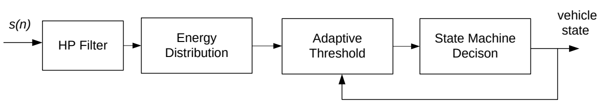


Fig. 8. Block diagram of SN operation.

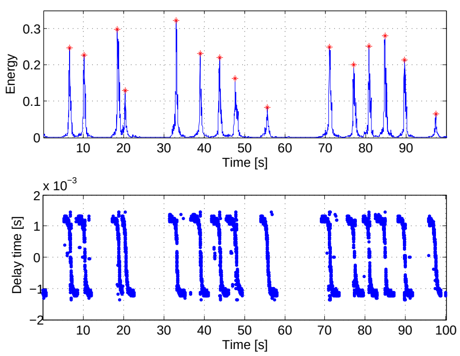


Fig. 9. Correlation between energy distribution and sound map.

Fig. 9 shows the result of this process compared with the sound map generated by the MN. It can be seen that the implemented algorithm is capable to detect, in this case, all the peaks of the energy distribution, as the vehicles are fairly spaced apart. In heavier traffic condition, however, the vehicle counting could be underestimated, but, in any case, the energy distribution represents an useful indicator to estimate the traffic flow in the carriageway.

V. Protocol Design

Main issues in Medium Access Control (MAC) and Routing protocol design are power consumption and the possibility of establishing a quick set-up and end-to-end communication. Other important features are *scalability* and *adaptability* of network topology, in terms of number of nodes and their density.

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.

TABLE I
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

According to the proposed MAC protocol, each node might be either in an idle mode, in which it remains for a time interval Tl (listening time), or in an energy saving sleeping state for a Ts (sleeping time). The transitions between states are synchronous with a period frame equal to Tf = Tl + Ts partitioned in two sub-intervals, as shown in Fig. 10

To provide the network with full communication capabilities, all the nodes need to be weakly synchronized, meaning that they are aware at least of the awaking time of all their neighbors. To this end, a node sends an HELLO message frame by frame to each of its neighbor nodes known to be in the listening mode (Synchronous Transmission), whereas, during the setup phase in which each node discovers the network topology, the control messages are asynchronously broad-casted.

On the other hand, its neighbors periodically awake and enter the listening state independently (Asynchronous Reception). The header of the synchronization message contains the following fields: a unique node identifier, the message sequence number and the phase, or the time interval after which the sender claims to be in the listening status waiting for both synchronization and data messages from its neighbors.

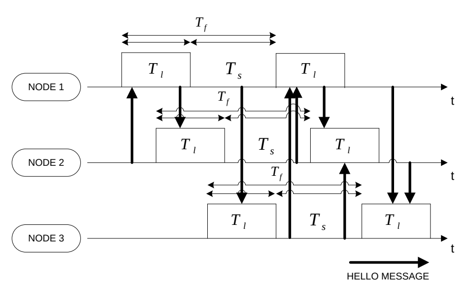


Fig. 10. MAC protocol HELLO message exchange

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 [10]. It is based on sending periodical information needed for building and maintaining the local routing tables depicted in Table I.

It resorts to the signaling introduced by the MAC layer with the aim of minimize the overhead and make the system more adaptive in a cross layer fashion.

VI. Experimental Results

First of all simulation experiments in laboratories has been performed to develop the proposed sensing method. Experiments were conducted using an acoustic signal recorded at an test site with the definitive sensor unit. Results of the simulation test and analysis are shown in the previous figures.

At the same time, the design of the hardware components is been carried out, in order to select the best arrangement of a prototype basic unit, allowing the sensing and processing operations, with the best cost-performance.

Finally, the prototype basic unit, has been deployed, along the Italian highway operated by Autostrade per l'Italia SpA (ASPI) near Florence. The basic unit was first installed on May 2009; since then it is operating collecting traffic parameters and is transmitting them to a central server. The prototype unit has been placed closely to a loop detector to test the MN operation.

During the long-term operation period, the system has detected various typologies of traffic condition under many environmental and weather conditions. Also the communication modality was tested successfully.

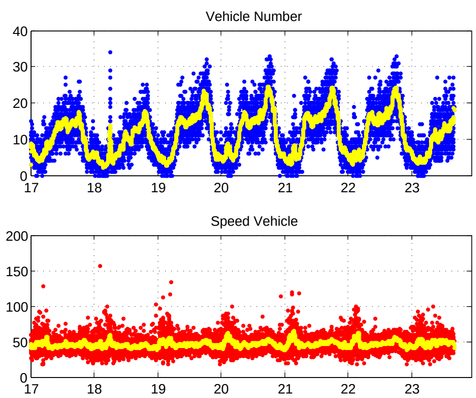


Fig. 11. Vehicle transit and average speed for a weekly observation slot.

Below, some of the collected data are presented; in Fig. 11 a weekly data collection related to vehicles transit and average speed is shown, highlighting the periodicity of the traffic flow with different behavior depending by day and hours.

The MN operation is validated by comparison with the loop detector. As is shown in Fig. 12, the two systems exhibit a good matching. The overestimation of the number of vehicles during the night is due to the background noise. For this purpose a specific post processing algorithm is under development.

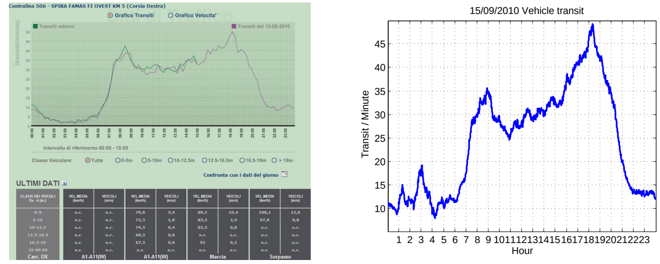
The MN reports are now fully integrated in the ASPI information system. SN reports are not yet available in graphic format. Extensive tests during the period of operation have provided the motorway practitioners with a complete reporting about traffic trends. Due to the yield and easy deployment of the 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 real-time traffic monitoring system, based on acoustic WSN has been proposed. The sensing technique is based on an array of acoustic sensors. The system is able to extract traffic parameters from the sound signals generated by the passing vehicles. System's nodes process sound signals locally on-site and transmit the collected information to a central server in order to be available for a remote user.

The signal processing algorithm and the vehicle detection procedure are described. Experimental results of long-time period operation are shown.

The developed system shows the following key features: (i) provides a complete picture state of the traffic flow at an larger scale and in real-time (ii) collect information coming from two different devices (iii) presents low installation and maintenance cost (iv) is able to large scale deployment.



(a) Loop Detector. (b) Audio System.

Fig. 12. Comparison between audio sensor and loop detector results.

References

[1] Klausner, A., Erb, S., Tengg, A., Rinner, B.:DSP Based Acoustic Vehicle Classification for Multi-Sensor Real-Time Traffic. Graz University of Technology, Graz, Austria.

[2] Forren,J. F., Jaarsma, D.:Traffic Monitoring by Tire Noise. Proc. IEEE Conf. on Intelligent Transportation System, Boston, MA, Nov 1997, pp. 177-182.

[3] Ding,J., Cheung, S.Y., Tan,C.-W., Varaiya,P.:Signal processing of sensor node data for vehicle detection. Seventh Int. IEEE Conf.Intell. Transp. Syst.

[4] Lopez-Valcarce, R., Mosquera, C., Perez-Gonzalez, R.:"Estimation of road vehicle speed using two omnidirectional microphones: A maximum likleihood approach", EURASIP J. Appl. Signal Process., p.1059 , 2004.

[5] Lo, K. W., Ferguson, B. G. :"'Broadband passive acoustic technique for target motion parameter estimation", IEEE Trans. Aerosp. Elect. Syst., vol. 36, p.163 , 2000.

[6] Cheung, S., Coleri, S. ,Varaiya, P.:Traffic Surveillance with Wireless Magnetic Sensors. University of California, Berkley. USA

[7] Knapp,C.H. , Karter,G.C.:The Generalized Correlation Method for Estimation of Time Delay. IEEE Transactions on Acoustic Speech and Signal Processing, Vol. ASSP-24, No. 4, August 1976, pp. 320-327.

[8] Chen,S., Sun,Z.P, Bridge,B.:Traffic Monitoring Using Digital Sound Field Mapping.IEEE Transactions on Vehicular Technology, Vol. 50, No. 6, November 200, pp. 1582-1589.

[9] 802.15.4-2003: part 15.4: Wireless Medium Access Control (MAC) and Physical Layer (PHY) Specifications for Low-Rate Wireless Personal Area Networks (LR-WPANs). IEEE Std., October 2003. [Online]. Available: www.ieee.org.

[10] Shakkottai, S., Rappaport, T., Karlsson, P.: Cross-Layer Design for Wireless Networks. IEEE Comm. Mag., vol. 41, pp. 74-80, October 2003.

