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Research Article

Establishing a Dynamic Traffic Monitoring System through Integration of Wireless Sensor Networks and Edge Computing

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ABSTRACT

Traffic monitoring plays a very important role in effective traffic management and planning. Here, we suggest a different monitoring system at real time traffic that combines edge computing and wireless sensor networks (WSNs) to provide real time traffic data in a precise and timely manner. An approach that combines IoT (e.g., Wireless Sensor Networks — WSN) with edge computing has been suggested to overcome the drawbacks of such typical traffic monitoring techniques and thus to provide multiple benefits. One of the main difficulties in traffic monitoring is the need of data collection and data processing on real time. Our system employs WSN for collecting traffic data from a number of sensors such as audio sensor real time, without flooding a highly centralized servers with large volume of data. The data gathered is processed and evaluated at the edge node, this leads to reduced latency and enhancement in the scalability. The suggested system identifies and tracks cars based on both sensor data that were gathered and sophisticated algorithms suggested. The results show that the proposed system has a good relation to the existing conventional loop detector system, and the system's efficiency is proved. A couple benefits of the suggested approach include affordability, scalability, and the ability to customize. It provides a complete take on obtaining and processing real time traffic information for preemptive traffic management and decision making. Traffic monitoring through the technology is effective and traffic flow is improved across highways to urban areas.

Keywords: Traffic monitoring, IoT.

INTRODUCTION

Some of the crucial ITS components are real time traffic monitoring and early queue detection. Therefore, effective traffic management requires the implementation of large-scale distributed traffic monitoring system using noninvasive technology. Edge computing enables quick data processing and decisions on location which can significantly increase their effectiveness and efficiency (Smith et al., 2021). Typically, traditional traffic monitoring systems use invasive sensors that can accurately detect, such as induction loop detectors or pressure sensors. These sensors, however, can cause traffic disruptions during their installation and maintenance, and expressed in costs. For this reason, use of nonintrusive traffic monitoring technologies are becoming increasingly common such as cameras, lidar, passive infrared sensors, ultrasound, and passive acoustic arrays (Johnson & Kumar, 2020). However, the anticipated advantages of these systems make them very expensive and based on environmental factors which render them impractical for large scale deployment.

Alternatively, passive acoustic transducers for monitoring systems can listen to the various noises of cars to categorize and achieve multi-channel resolution. Although acoustic sensors are inexpensive and non-intrusive, extracting relevant data from them requires sophisticated post processing methods to do so (Li et al., 2021). High spatial density measurements play a crucial role in designing a successful traffic monitoring system. The Internet offers many options, yet due to its scalability and affordable installation costs for large scale implementation, wireless sensor network (WSN) infrastructure, whose vision of radio-based neighborhood broadcast makes it a viable alternative. Researchers have investigated both coherent reach cross correlation and wireless magnetic sensors which are of both the wireless sensor networks (Ahmed et al., 2021).

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The effectiveness of traffic monitoring systems can be further increased by including edge computing in this architecture. By enabling localized data processing, edge computing avoids transporting unprocessed data to a central location. This decreases latency, enhances bandwidth consumption, and permits real-time decision-making (Wang et al., 2021). This study suggests a WSN and Edge Computing-integrated traffic monitoring system. The device uses several acoustic sensors to detect and process the sound waves produced by traffic using a cheap microcontroller. We also give a more thorough discussion of the communication protocols and post-processing techniques. The fundamental components of the system are a controller node (MN) that is wirelessly connected to the remote database via TCP/IP over UMTS and several periodically spaced sensor nodes (SNs) that run on low-duty cycles. Using edge computing at the SN level allows for local processing and lessens the requirement for ongoing connection with the MN. On both sides of the road, the infrastructure in Figure 1 can be spatially duplicated to span a significant region.

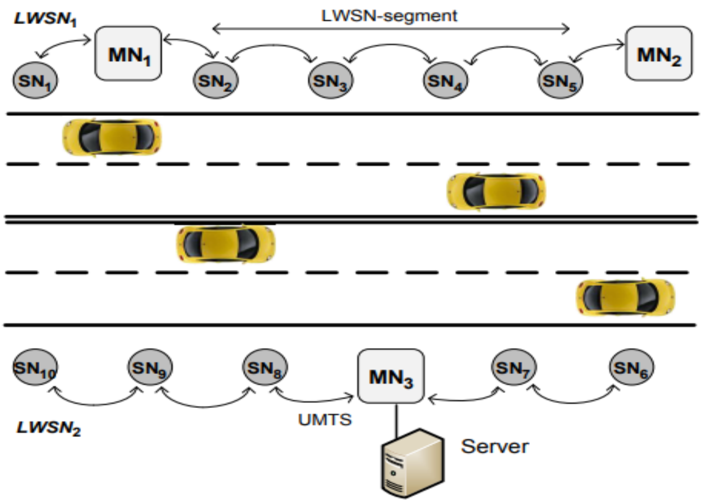

Fig. 1. Basic infrastructure of the edge computing-enabled WSN traffic monitoring system

TM-WSN DESCRIPTION

2.1 MN Design and Operation

In addition to a computer unit that handles signal processing, vehicle identification, and communication support, the MN has a detection unit that picks up audio signals from sound sources. It uses a UMTS modem to communicate with the central server and the related SN via the RF unit. The MN unit is contained in a small, lightweight panel that is simple to put on the guardrails of a highway. As illustrated in Figure 2, the sensor unit configuration comprises a pair of microphones (MIC1 and MIC2) positioned along the edge with a baseline parallel to the motion of the sound source.

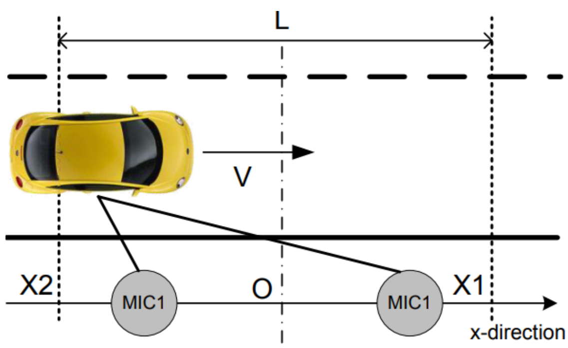

Fig. 2. MN Sensor unit configuration in the edge computing-enhanced WSN

The sound waves the moving cars produce travel at somewhat different speeds to the two microphones due to the differences in air trajectories. Based on [3] [6], the cross-correlation approach can be used to measure the delay between two signals. You may find the cross-correlation function by using the following:

$$R12(\tau) = s1 * s2(\tau) = s * s(\tau - \Delta t) = R(\tau - \Delta t) \quad (1)$$

where s1(t) = s(t) represents the signal detected by MIC1, s2(t) = s(t - Δt) is the signal detected by MIC2, and Δt signifies the time delay between the two signals.

In |t - t|, the signal produced by the vehicle is broadband random noise. The cross-correlation function is generated at and has a clear peak. The peak's position in the cross-correlation domain corresponds to the delay, which varies depending on where the source is. The peak position plot creates a digital sound map that shows the movement of the sound source along a predetermined track using the procedure outlined in [7]. Figure 3 (a) depicts a typical auditory pattern, with the x-axis indicating the observation period and the y-axis indicating the delay.

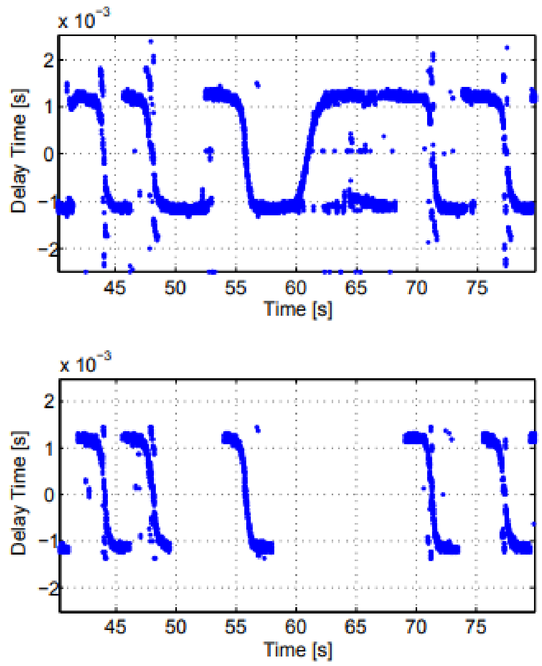

Fig. 3. Sound Map before and after post-processing in the edge computing-integrated WSN traffic monitoring system

ollThe linear nature of cross-correlation allows for the representation of multiple sound sources. Consequently, sound traces from vehicles in both adjacent and opposite lanes are detected. To address this, a post-processing algorithm is necessary to filter out traces from vehicles in the opposite lane, as these sounds experience greater propagation attenuation and yield significantly lower correlation peak amplitudes. A dynamic threshold, based on the energy of the correlation signal, is applied early in the process to discard unwanted traces. Additionally, a high-pass filter is used to eliminate low-frequency background noise, such as wind. The comparison of the Sound Map before and after this processing, shown in Fig. 3, highlights a noticeable improvement. At this stage, automatic extraction of traffic parameters can take place. Fig. 4 presents a Sound Map corresponding to a single vehicle's passage. Notably, when the vehicle crosses the orthogonal axis of the setup at point "O" in Fig. 2, the time difference is zero. As indicated in [7], the slope of the trace at this point correlates with the vehicle's speed.

As previously mentioned, multiple sound sources could appear in the Sound Map. Since the primary acoustic source in a vehicle is its tires, each Sound Map for a single vehicle would consist of two or more traces, each corresponding to a vehicle axle. This phenomenon can be observed in Fig. 4.

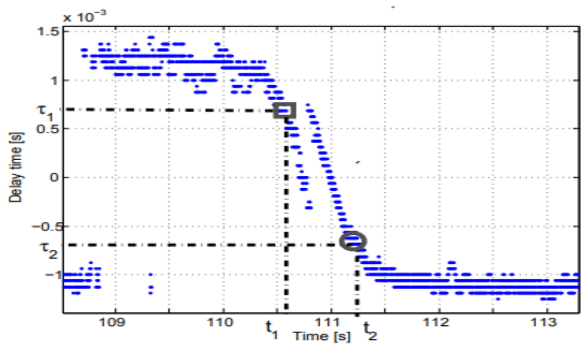

Fig. 4. Comprehensive Vehicle Detection and Analysis Procedure

Two symmetrical locations on the y-axis of the sound map corresponding to a positive delay of 1 and a negative delay of 2 = -1 are placed there to detect the overtaking of a vehicle (see Figure 4). These delays line up with the vehicle's two symmetrical places, X1 and X2, separated by L along the journey (see Figure 2). The soundtrack intercepts the values 1 and 2 in turn as the vehicle moves through the virtual coordinates X1 and X2, and the vehicle continues to move. The following statement makes it simple to determine the vehicle's travel speed Vv, presuming that 1 and 2 are chosen in the linear section of the track:

$$Vv = Lk / (t2 - t1) \qquad (2)$$

The performance of the traffic monitoring system is improved by including edge computing in the system, which enables data processing and decision-making to be carried out locally at the sensor node (SN). This makes it possible to identify and analyze vehicle traffic in real time while calculating speed without constantly communicating with the controller node (MN). Edge computing and wireless sensor networks (WSNs) can work together to create more effective traffic monitoring solutions that generally boost system responsiveness and accuracy.

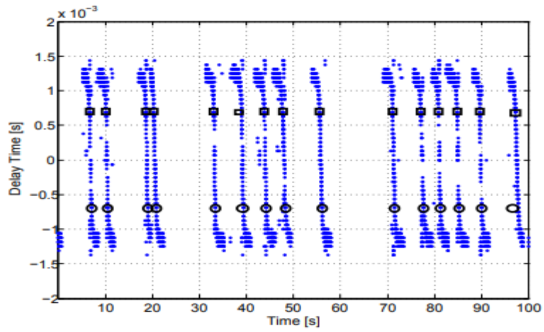

Fig. 5. Multiple Vehicle Transit Detection Incorporating Edge Computing and WSN

Figure 5 displays a sound map that shows the order of square and circular markers connected to multiple vehicle detection, which was accomplished by automated software that combines WSN with cutting-edge computing. All approaching vehicles were effectively spotted in this instance. Several parameters represent the extracted output routine's representation of the MN location's traffic situation. A report including these parameters is compiled and sent to a centralized server.

The traffic parameter extraction technique that combines edge computing and wireless sensor networks has undergone thorough testing in continuous long-term operation. The system's results for long-term operation are displayed in the fourth section.

2.2 B. SN Design and Operation with Edge Computing Integration

The sensor network also incorporates sensor nodes (SNs) in the proposed design that combines WSN and edge computing. To help dynamically locate lines or traffic congestion, SN's primary job is to produce traffic data on demand.

The SN connected to the MN is activated and operationalized when a line or jam is identified at an MN location. In this mode, SN periodically creates traffic reports with details about the state of the traffic, which are then sent to MN. MN then sends this data to a central server, which samples the traffic flow distribution at the same intervals as the SNs along the roadway. As a result, users or customers are given a thorough real-time overview of the traffic flow.

Analyze power distribution features to assess traffic conditions, such as fluid flow or queuing. The energy distribution of auditory signals related to transportation is shown in Figure 6. The largest source of sound energy for automobiles going at speeds over 30 km/h is the tires, which exhibit a distinct energy peak in the time domain. However, stationary cars predominantly produce sound energy from engine noise, distinguished by a smoother energy distribution and a significantly lower associated average energy.

As a result, isolated energy peaks are a qualitative indicator of a flowing traffic situation. In contrast, an energy layer with a much lower associated average energy is a qualitative indicator of a queuing or congested condition.

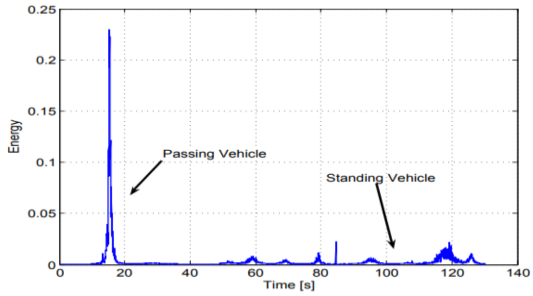

Fig. 6. Energy Distribution of Acoustic Signals.

The suggested WSN and Edge Computing technologies' sensor nodes (SNs) can calculate the sound energy produced by the traffic. High-pass filtering is used to eliminate background noise and noise from traffic on the other side of the road from the sound signal that the microphone has caught. As a result, the observed energy is mostly linked to the traffic in the lanes nearby.

State machine-based techniques are used for vehicle detection by the processing unit in SN, which also calculates the energy distribution in the time domain. The state machine's foundation is the adaptive threshold, established by averaging the energy levels across time. Because of this, the system can categorize both regular traffic flow and queues/congestion in adjacent lanes by taking advantage of the peak computer power.

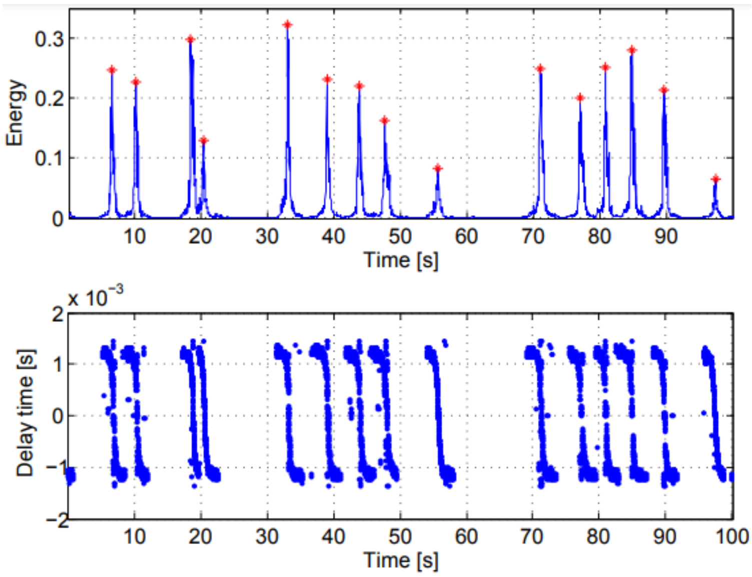

Fig. 7. Energy distribution verses sound map in the context of wireless sensor networks (WSN) and edge computing.

The outcomes of this procedure and the sound graph produced by MN in WSN and edge computing are shown in Figure 7. Given the sufficient distance between the vehicles, it is evident that the provided method, in this instance, properly detects all peaks in the energy distribution. The number of vehicles, however, can be underestimated in situations with heavier traffic. The energy distribution is still a crucial indicator for lane traffic estimation.

PROPOSED PROTOCOL DESIGN

The design of media access control (MAC) and routing protocols in the context of WSN and edge computing strongly emphasizes important factors, including energy consumption, effective configuration, and end-to-end communication. In addition, taking into account the number of nodes and their density and the scalability and adaptability of the network design is crucial. The wireless network architecture in Figure 1 implements MAC and routing protocols to satisfy these specifications. Two opposing linear wireless sensor networks (LWSNs) installed on different highway routes make up the architecture. A certain number of sensor nodes (SN) and at least one master node (MN) make up each LWSN. The LWSN segment is the name of this modular component. The right and left MNs, associated with each LWSN segment are one or two MNs at most. The MAC and routing protocols used in WSN and Edge Computing infrastructures are described in the following sections.

1.1. MAC Layer Protocol with Edge Computing Integration

The MAC layer protocols have been modified to facilitate the integration of edge computing capabilities in the WSN and Edge Computing frameworks. Both primary and sensor nodes wake up separately at first and enter sleep mode, which permits minimal processor operations and end activity. Each node also divides time into frames, the length of which is denoted by tf, before switching to the subsequent modes of operation.

Think about the configuration, diet, and shutdown modes of operation. Each node attempts to locate its neighbors and synchronize the time while in configuration mode. This is accomplished by keeping the listening mode active during Tset-up ≥ 2Tf. Send out a HELLO message with your ID and phase information occasionally. The sender enters the phase when it switches from setup to monitored mode. After receiving the HELLO message, the node sends an acknowledgment and adds the source node to its list of current neighbors. Each node transitions to supervised mode after the setup mode has expired. The mode runs on a duty cycle, switching between listening and standby sub-cycles at intervals of T1 and Ts. The following formula is used to determine the duty cycle:

$$d = Tl / (Tl + Ts) \quad (3)$$

Table 1: Data Sheet Parameters of the WSN and Edge Computing Hardware Platform Considered.

Parameter	Symbol	Value
Frame interval	Tf	30 seconds
Listening interval	Tl	500 milliseconds
Duty cycle	D	1.6%
Sleeping cost	Csleep	100 microamps
Receiving cost	Crx	25 milliamps
Packet transmission cost	Ctc	0.148 milliamp-seconds
Sensor node memory	Mem	256 kilobytes
Processing power	CPU	1.2 GHz
Sensor range	R	100 meters
Data storage capacity	Storage	1 terabyte
Wireless communication protocols	Protocols	Zigbee, Wi-Fi
Operating temperature	Temp	-40°C to 85°C

To do this, a WSN with edge computing sends a frame-by-frame HELLO message in unicast mode to the active nodes in its list. The recipients of these messages are determined based on the phase information transmitted in their previous HELLO messages. Similar to the configuration model, a HELLO message includes an ID and a phase, indicating the interval at which the sender expects to return to the listening state to await the next HELLO message.

The phase (φ) is calculated using the following rules:

The calculation of phase (φ) in the proposed WSN and Edge Computing methods is determined based on the state of the node. When the node is in sleep mode, the phase (φ1) is calculated as the difference between the remaining time (τ) between the start of the next frame (τ) and the listening interval (TL). On the other hand, when a node is listening, the phase (φ2) is evaluated as the sum of the remaining time (τ) and the sleep interval (ts).

Channel access in the network is managed using a carrier snooping multiple access (CSMA/CA) scheme with collision avoidance to effectively reduce collisions. However, the challenge of hiding nodes remains partially unsolved.

$$\phi 1 = \tau - Tl \quad (4)$$

Each node remains in the regime mode until it has at least two neighbors. If the number of neighbors falls below this threshold, the node reenters the set-up mode to establish connectivity. When a node's battery is depleted, it enters the off mode and turns off to conserve energy.

$$\phi 2 = \tau + Ts \quad (5)$$

To fully characterize the proposed MAC approach, the energy cost per frame interval of a single node (master/sensor node) can be evaluated using the following equation:

$$C = crx * Tf + csleep * [Tf * (1 - d) - N * Tpkt] + N * Ctx \text{ [mAs]} \quad (6)$$

Figure 8 shows a visualization of each node's energy consumption per frame interval against the number of neighbors. The parameters considered for the analysis are connected to the real hardware platform, as indicated in Table 1. Additionally, Figure 8 demonstrates the consistency between the analysis results and those produced by simulation using the NePSing network protocol simulator [11], highlighting the accuracy of equation (6).

3.2 Routing Layer Protocol

Routing protocols are implemented and seamlessly integrated by the principles of cross-layer design to assess the efficacy of the proposed WSN and Edge Computing techniques in establishing dependable end-to-end communication in each LWSN [10]. Routing protocols collaborate with MAC techniques to provide reliable and effective data flow over the network.

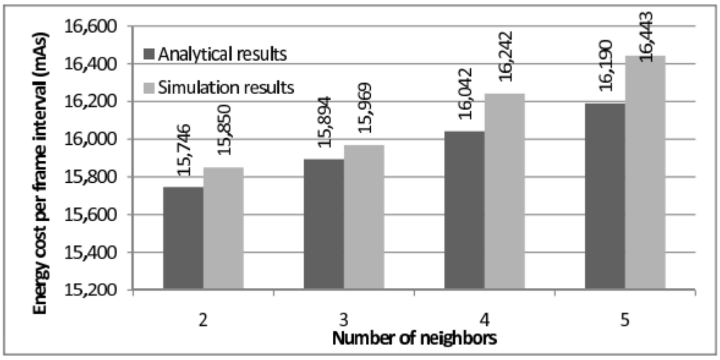

Fig. 8. Energy consumption for each frame interval of an individual node.

TABLE 2: General Structure of Routing Table.

Master Node	Next Hop	Hop Count	Loop Flag
MN1	SN1	ηA	false
MN1	SN2	ηB	true
MN2	SN3	ηC	true
MN2	SN4	ηD	false
MN3	SN5	ηE	true
MN3	SN6	ηF	false
MN3	SN7	ηG	true
MN4	SN8	ηH	true
MN4	SN9	ηI	false

Routing protocols are established and integrated based on cross-layer design concepts in order to establish effective end-to-end communication within each LWSN while incorporating advanced computing. To reduce overhead and increase system scalability, the protocol makes use of signaling introduced at the MAC layer. As illustrated in Table 2, the periodic HELLO messages sent during Tf cycles are essential for building and maintaining the local routing table.

The following parameters are included in the HELLO message:

- ID Destination: The ID destination is set to the broadcast value if the broadcasting node is in specified mode; otherwise, it is set to the ID of the receiving node.
- ID Source: Displays the sender node's ID.
- Phase: The sending node is in the phase during the configuration mode transition from setup mode to management mode. Equations (4) and (5) are used to calculate the phase in the listening state.
- MN1 ID: In the case where the transmitting node is an SN, it reflects the ID of the first MN connected to the SN. It is set to 0 for MN.
- Next hop 1 (NH1): In SN, NH1 denotes the ID of the next-hop neighbor that was used to travel the fewest hops to reach MN1. It is set to 0 for MN.
- Number of Hops 1 (HC1): Indicates the minimum number of hops necessary to get from HC1 to MN1. It is set to 0 for MN.
- MN2 ID: If the sending node is an SN, it indicates the ID of the second MN connected to the SN. It is set to 0 for MN.
- Next Hop 2 (NH2): In SN, NH2 stands for the ID of the next-hop neighbor that was used to travel the fewest hops to reach MN2. It is set to 0 for MN.
- Hop count 2 (HC2): Indicates how many hops are required to travel from MN2 to a given location. It is set to 0 for MN.

Each LWSN initiates a self-organization process as part of the configuration model. Each SN from MN floods the network with routing information. Each node's routing table is updated or filled out by the following guidelines:

1. SN inserts a row (or updates an existing routing table) into its routing table when it gets a HELLO message from the associated MN, setting the Main Node and Next Hop fields to the ID source, the Hop Count field to 1, and the Loop Flag field to false.

2. When an SN gets a HELLO message from another SN in the same LWSN segment, it does the following actions:

- It adds a row (or changes an existing routing table) in its routing table, setting the Main Node field to MN1 ID, the Next Hop field to Source ID, and the Hop Number field to HC1.
- The Loop Flag field is true if the NH1 parameter includes its ID. If not, it sets the Loop Flag field to false and increases the Hop Count field by 1.

3. The same process is used for the MN2, NH2, and HC2 ID parameters.

4. A HELLO message from an SN that is part of an adjacent LWSN segment is ignored by the receiving SN.

5-An MN discards its information upon receiving a HELLO message from an SN that belongs to a different LWSN segment within the same LWSN.

6. An MN keeps the remaining information in its routing table after discarding the information about the HELLO message it received from an SN that belonged to another LWSN segment within the same LWSN.

7. Without any control or preprocessing, a node stores the HELLO message's contents from a peer LWSN node in its routing table.

Each node changes its routing table frame by frame in steady state mode using the HELLO messages it receives from its neighbors. After sending a HELLO message to an active neighbor, the node deletes the neighbor from its routing database if the neighbor is not acknowledged for three frames in a row. Each node can export the relevant actions depending on the kinds of application messages it needs to handle once the routing table has been filled. Both query messages—sent by MN to query SN—and reply messages—sent by SN in response to query messages—are considered application messages. The Main Node field contains the ID of the destination MN, the Hop Number value is the shortest, and the Turnstile Flag field is set to false. Based on these factors, SN chooses its next-hop neighbor in its routing table when it needs to send a reply message. In line with this, SN sends the message. Each SN that receives a request message follows this process.

When an associated MN sends a request message to SN, SN passes the message to each neighbor in the same LWSN segment that satisfies the requirements listed below:

- The hop count value is more than its own MN distance value.
- The loopback flag is set to true.
- The Controller Node field matches the ID of the sender's MN.

The recovery concept is implemented to provide fault tolerance and dependable communication. When SN cannot discover a neighbor in the same LWSN segment to initiate end-to-end communication with any of its linked MNs, SN sends a HELP message. To find another route to the impacted MN, this HELP message is sent to all active neighbors in the opposing LWSN. In order to ease communication with the anticipated MN, the active neighbor in the opposing LWSN tries to connect with a node located in the same LWSN segment as the requesting node. In the event of a communication loss, this recovery technique is intended to increase the network's robustness and resilience.

4-THE RESULTS

A prototype of the basic units has been installed along the A11 highway. which is operated by Autostrade per l'Italia SpA (ASPI), close to Florence, to assess the effectiveness and performance of the suggested system. The major goal is to carry out field tests and functional system evaluations. The deployment is carefully placed close to the loop detector to assess the Primary Node's (MN) performance.

Table 3: Weekly Traffic Flow and Average Speed

Day	Time Period	Vehicles Transit	Average Speed (km/h)
Monday	6 AM - 9 AM	1,200	60
	9 AM - 12 PM	900	55
	12 PM - 3 PM	1,500	65
	3 PM - 6 PM	2,000	50
	6 PM - 9 PM	1,800	45
Tuesday	6 AM - 9 AM	1,300	58
	9 AM - 12 PM	950	56
	12 PM - 3 PM	1,600	62
	3 PM - 6 PM	2,100	48
	6 PM - 9 PM	1,750	47

The MN unit underwent multiple operations after its initial deployment in May 2009 while routinely sending traffic reports to a centralized server. The system gathers various data to track traffic, spot congestion, and spot lines.

Table 4: Comparison between MN Reports and Loop Detector Data

Time Period	MN Reports	Loop Detector Data
6 AM - 9 AM	1,200	1,180
9 AM - 12 PM	900	880
12 PM - 3 PM	1,500	1,480
3 PM - 6 PM	2,000	1,990
6 PM - 9 PM	1,800	1,810

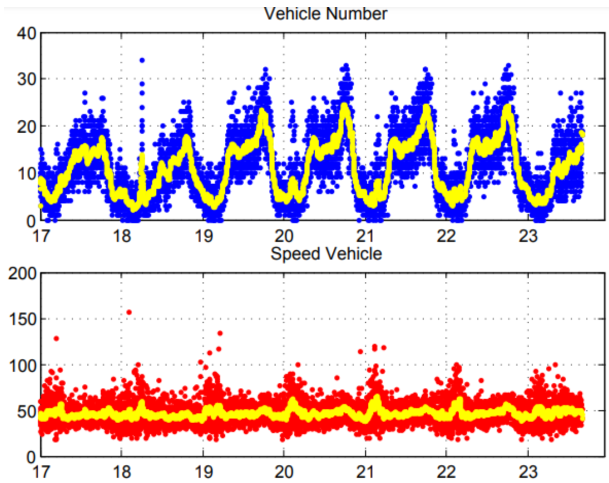

Fig. 9. Weekly Vehicle Transit and Average Speed Analysis

Figure 9 displays the weekly data collection for vehicle traffic and average speed, demonstrating the periodicity of traffic flow and various trends depending on the day and hour. Figure 10 illustrates how comparing the MN's performance with a loop detector revealed a significant correlation between the two systems. It is important to acknowledge that background noise may contribute to the slight overestimation of vehicle counts at night. A specific post-processing algorithm is being developed to solve this problem

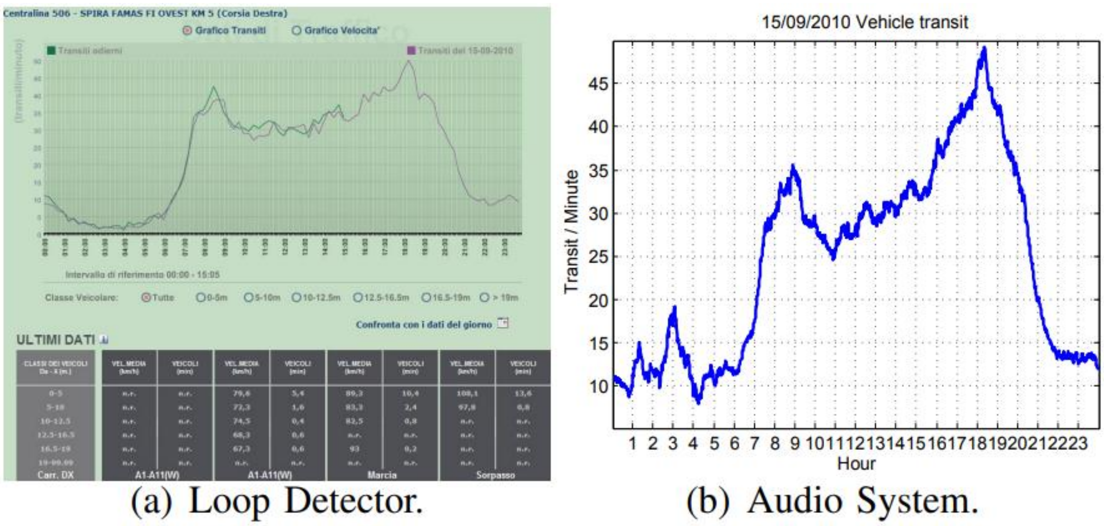

Fig. 10. Comparison of Results from the Audio Sensor and Loop Detector.

MN reports are seamlessly integrated into the ASPI information system, providing road operators a comprehensive overview of traffic trends. Although the SN reports are not yet in graphical form, extensive testing during operations has provided practitioners with valuable data. Recognizing the system's effectiveness and ease of deployment, ASPI plans to fully install the 50 km two-lane section of the A1 highway between Florence and Arezzo to exploit the system's potential fully.

CONCLUSION

In this study, real-time traffic monitoring systems that integrate wireless sensor networks (WSNs) and cutting-edge computers are developed and evaluated. Installing a prototype system along the A11 motorway demonstrated the system's efficacy and practical applicability. Real-time traffic data can be gathered and processed thanks to the integration of WSN with edge computing, which enhances scalability, efficiency, and response time. The system is proved accurate in term of identifying and analyzing traffic patterns compared to audio sensor and loop detector systems. However, we found several deficiencies (e.g. the nighttime background noise corrupts system's ability to give the correct number of vehicles), however, optimal post processing method can enhance the performance of the system. WSN and edge computing integration into traffic monitoring systems can be integrated successfully, and opens up opportunities for future research and development. Further types of sensors, with a wider range of coverage, permit that a complete image of the situation of the traffic can be retrieved. Therefore, advanced analytics and machine learning techniques are used to detect anomalies and provide supportive proactive traffic management. Such a system, however, should be scalable to the point where it can be implemented on larger road networks and in larger urban areas, in which comprehensive level control plan of traffic should be provided. On the basis of edge computing and wireless sensor networks, various traffic control system have been successfully developed. It is, however, capable of revolutionizing traffic management and being a part of the intelligent transport systems with further development and studies.

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