Using Radio Irregularity for Vehicle Detection in Adaptive Roadway Lighting

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Abstract – The need to reduce power consumption makes a great impact in the world of roadway lighting. The adaptive lighting is now used to define the concept of varying the levels of lighting in order to significantly reduce the consumed power. In this paper a novel approach in vehicle detection and tracking using WSN (Wireless Sensor Networks) radio irregularity is proposed for use in adaptive roadway lighting. Radio irregularity is a common phenomenon which arises from multiple factors and is considered a shortcoming of wireless communication. However, this phenomenon can be exploited for detecting obstacles in the propagation path, such as vehicles on roadways. The idea is based on monitoring RSSI (Received Signal Strength Indicator) between WSN nodes, where the propagation path intersects the roadway. The method is analyzed experimentally using XBee Series 2 modules in different scenarios and the comparison is given. The advantage over the existing detection methods is the reduction in cost by avoiding the need to additionally install multiple sensors for vehicle detection.

I. INTRODUCTION

An important aspect of energy saving is reducing power consumptions in roadway lighting. By correct investments and utilizing new technology it is possible to reduce current energy consumption for street and road lighting by as much as approximately 60%. For Europe as a whole, this stands for about 36TWh a year. In addition, it is possible to achieve a significant saving on maintenance costs. As much as 50-70% of the original energy consumption can be saved by investing in new technologies for roadway illumination [1].

One of these technologies includes adaptive lighting technology. The term “Adaptive Lighting” is now being used to define the concept of varying lighting levels to suit activity levels. By varying the levels of lighting on roadways, substantial power can be saved [2]. By implementing the intelligence into luminaries it is possible to achieve accurate feedback on the lamps condition and thereby reduce the need for manual control [1]. Also, the management of the installed lamps is done remotely, enabling the supervision of the entire lighting system and dynamically changing the required illumination levels.

The induced intelligence to the luminaries brings a set of advantages to the proposed system. Primary, the supervision of all luminaries from a control center is possible, alongside with remote diagnostic and failure reporting. Further on, the control of the luminaries is possible by dimming the lamps or an array of lamps, to suit the current activity levels. In order to interconnect the luminaries, the most common approach in the use of WSN (Wireless Sensor Network) [3, 4].

Primary task of the adaptive roadway lighting is adjusting lighting levels depending on the amount of traffic, time of day and weather condition, in purpose of reducing power consumption [1]. According to [5], dimming of the roadway lighting does not influence the visibility of drivers, allowing the implementation of an adaptive lighting system.

In order to utilize the benefits of adaptive roadway lighting, a cost effective way of detecting vehicles and amount of traffic must be proposed. The existing methods include setting up inductive loops or other proprietary sensors, presenting a costly solution for a large number of units. Since the adaptive lighting system already uses WSN for data exchange, this paper proposes the use of WSN wireless links for vehicle and traffic detection, by the means of radio irregularity.

The paper presents a novel method of vehicle detection by monitoring RSSI (Received Signal Strength Indicator) values from ZigBee or IEEE802.15.4 nodes where the propagation path is intersected by the roadway. Once a vehicle intersects the propagation path, the drop in RSSI value is evident. This drop correlates with the size and speed of the vehicle, so a model is proposed to determine the required setup for the detection.

The measurement of the proposed method is shown in various different scenarios. In order to detect vehicles traveled at higher velocities, the adaptation of the proposed detection method is shown. The testing was carried out using ZigBee WSN nodes, specifically Digi’s XBee Series 2 modules. The calculation of the maximum detection speed and the RSSI attenuation is done from a theoretical aspect, following by the comparison of the measured values.

In the following section, the basic concept of adaptive roadway lighting is presented. Also, the proposed vehicle detection is placed into the frame of adaptive roadway illumination (statistically measuring amount of traffic and dynamically anticipating movement). Section III proposes the theoretical and practical implementation of vehicle detection using radio irregularity, while Section IV shows the results of the measurement in a rural area. Section V gives the conclusion alongside with the future work suggestions.
II. THE CONCEPT OF ADAPTIVE ROADWAY LIGHTING

In order to understand the concept of adaptive roadway lighting one must understand how road light levels are typically determined. Light levels for roadways and pedestrian traffic are established through engineering design by applying minimum criteria based on the type of roadway and level of pedestrian activity [2]. According to [6], the ANSI/IES RP-8 document proposes minimum luminance levels for different types of roads and different pedestrian activities (Figure 1).

Pedestrian activity (conflict) levels do not necessarily remain constant throughout the hours of darkness, taking into consideration that in late evening and early morning hours the businesses are closed, thus reducing the number of pedestrians [2]. Another important fact to examine is the presence and frequency of traffic on a designated road. This primarily encompasses the rural areas where the traffic frequency tends to drop rapidly in late evening hours. Due to this fact, and the fact that the pedestrian activity tends to drop as well, the implementation of adaptive roadway lighting in these areas could significantly reduce power consumptions. Also, according to [5], dimming of the roadway lighting does not influence the visibility of drivers. With this, the road safety is preserved, allowing for the implementation. This is supported by the work done in [25], where the comparison of various adaptive illumination projects is given. By implementing adaptive roadway lighting, the safety of road condition is generally improved [25].

The implementation of adaptive lighting in rural areas with the advancement of cost effective vehicle (traffic) detection could be performed in two different approaches. This paper proposes the following approaches:

- The first approach is the statistical approach: The system measures statistical amount of traffic throughout the day and compensated by weather condition parameters predicts the necessary illumination levels for the next time period (several hours or an entire day). The main advantage of this method is constant traffic monitoring providing statistics that change by the hour. Further on, the detection system doesn’t have to be very reliable regarding vehicle detection (a drop in vehicle detection is tolerated to a certain degree), however the system must be able to tell apart vehicles from pedestrians and other objects. On the other side, the proposed system uses only statistic parameters, meaning that real-time reactions are not supported.

- The second approach utilizes real-time monitoring of traffic and pedestrian activates, and adaptively corrects the lighting levels. If no vehicles are present in the range of the luminary’s network segment, the lighting levels are mitigated due to the reduced pedestrian risk (lack of vehicles). When the system detects a vehicle in range of the luminary network segment, it predicts the movement of a vehicle and accordingly raises the luminance levels along the vehicle propagation way, discreetly following the vehicle along the rural settlement (Figure 2).

The advantage of this system is the real-time operation and the ability to reduce power when no vehicles are present in the area. The system can be designed to detect pedestrian presence, thus additionally reducing the risk to the pedestrians. However, this type of system proposes additional load on the system due to the fact that the system needs to operate in real-time and the detection of vehicles in the network must be very reliable (the system must detect every passing vehicle).

Each approach presents its own advantages and drawbacks and the choice of approaches and systems must be presented according to the studies developed for this specific approach. On the other hand, vehicle detection can also dictate the choice of presented approaches, depending on the reliability of vehicle and pedestrian detection. The proposed method of vehicle detection is a novel approach that needs to be analyzed and a conclusion of the practical use of the proposed method should be assessed.

A. Wireless Sensor Networks in Adaptive Roadway Lighting

Wireless Sensor Network (WSN) is a wireless network consisting of sensing, computing and communication elements that gives the ability to instrument, observe and react to events and phenomena in specified environment. Typical applications include data collection, monitoring, surveillance, medical telemetry and others [9], such as adaptive lighting.

Upon discussing communication protocol used in WSN, ZigBee is one of the most frequently used protocols. It is designed for use in personal networks of low bandwidth, low power consumption, low cost and high level of security [9]. Forming a ZigBee WSN has many advantages, foremost the ability to route data packets along the mesh network to the desired end node (multi hop routing [10]. This presents a major advantage in the adaptive roadway lighting, since the network topology is as such that multi hop routing is essential (seen in Fig. 2).
On the other hand, the problem with using a ZigBee based WSN is the need for centralized network control. In ZigBee network, the Coordinator establishes an entire network, and all nodes must answer to the coordinator. This presents a problem in Adaptive Roadway Lighting, since all nodes needs to answer to the coordinator. This could be avoided by using protocols such as IEEE 802.15.4 and DigiMesh [12]. These protocols support P2P (peer-to-peer) routing, giving the option to exchange messages between the nearby sensors. The example of the topology used is shown in Fig.3.

![Figure 3. Dynamic Street Illumination network topology [12]](image)

In order to connect the network to the Internet, an intelligent gateway is used. The DigiMesh intelligent gateway provides a connection to the Central control room by means of Internet or Cloud based communication. The access technology can vary, such as 3G, Wi-Fi or Satellite communication [12]. The solution proposed by [12] is the interconnection of WSN to the Cloud infrastructure by the means of ConnectPort X4 or ConnectPort X5 devices. These devices contain the hardware to connect the WSN to the Internet (via 3G, Wi-Fi etc) and relay the data to the iDigi Cloud service. From the application point of view, the cloud presents an aggregation point for all data. The data is easily accessed from the cloud, where the need for device addressing or establishing communication is avoided.

Since the WSN is the backbone for establishing communication in adaptive roadway lighting, this paper proposes the novel method using WSN for vehicle detection by means of radio irregularity.

### III. USING RADIO IRREGULARITY FOR VEHICLE DETECTION

Radio irregularity is a common phenomenon in wireless networks. It can arise from multiple factors, such as the different signal radiated powers caused by hardware imperfection and the different path losses in different directions of transmitted signal [13]. According to [14], radio irregularity is mainly caused by device properties and the propagation medium. Device properties include SNR (Signal-to-Noise Ratio), the antenna gain, antenna type, the receiver’s sensitivity and threshold and the transmitter’s radiated power. Medium properties include the background noise and the environmental factors such as obstacles within the propagation medium.

The variations in the signal path loss can also cause the radio irregularity. When the signal travels through a medium, it may be diffracted, scattered or reflected. Diffraction occurs when the signal encounters an irregular surface. Scattering occurs when the signal propagates through a medium which contains a large number of objects smaller than the signal’s wavelength whereas reflection occurs when the signal during its propagation through a medium encounters an object which is larger than the signal’s wavelength [13, 14].

The variations in RSSI (received signal strength indicator) caused by radio irregularity are especially expressed by the presence of a large conductive object in the propagation path between two WSN nodes, which vehicles are. Since vehicles consist mostly of conductive material (sheet metal, iron, steel, aluminium) and exhibits the dimensions much larger than the wavelength of WSN communication (4.5m for a vehicle vs. 0.125m for wavelength), the main cause of radio irregularity are reflection and scattering.

According to various sources [13, 15, 16 and 17] the detection of human presence by the means of radio irregularity is well documented, and it is confirmed that the detection of human presence in-between propagation path using radio irregularity is possible. However, a similar approach in vehicle detection using radio irregularity was not pursued by any researchers. Related work consists of detecting the attenuation and packet loss in VANET (Vehicular Ad-Hoc Network) networks [18]. Mostly the work was focused on using the WSN as a data relay network and using specific sensors for vehicle detection (magnetic, acoustic etc) [19, 20]. Supported by the work for human presence detection, this paper proposes the use of radio irregularity in ZigBee or IEEE802.15.4 based WSN for purpose of vehicle detection.

### A. Theoretical aspects of vehicle detection using radio irregularity

The main claim for supporting the detection of vehicles using radio irregularity is the reflection and scattering effect that a vehicle has on a propagation signal. This results in the drop of RSSI value during a pass of a vehicle. The depth of the signal mitigation is dependent on the type of vehicle and distance between nodes but the duration of the drop is in correlation with the speed of a vehicle. Due to the fact that every vehicle is different in geometry, analytically representing the depth of the RSSI drop presents a problem. On the other hand, the duration of the RSSI drop is in direct correlation with the vehicle speed, the proposed propagation path and the width of the 1st Fresnel zone.

Due to the fact that the ZigBee and DigiMesh WSN is digital based network, all communications are sent in packet form in timed intervals. The fact that for the RSSI value to be obtained, the communication must be established to a nearby node imposes a delay that defines maximum sampling rate of RSSI value. This presents a problem for moving obstacle detection, due to the fact that for faster moving object the detection can skip the vehicle do to the low sampling rate. Do to this fact this paper proposes the adaptation of the detection model based on maximum possible velocity an object can achieve. The adaptation is based on widening the width of the 1st Fresnel zone, extending the effective length of a vehicle. The
effective length is the result of the propagation link and 1st Fresnel zone in conjunction with the length of a vehicle. If the detection is performed in a form of a laser beam sampled at a rate $f_s$, and the vehicle passing through the beam has the length of $l$, then the maximum vehicle speed this system can detect is:

$$v_{\text{max}} = l \cdot f_s$$  \hspace{1cm} (1)

However, if a detection system is not composed of thin beam (as a laser beam is thin compared to a car) but a wide spatial beam (the width of the 1st Fresnel zone), then the length $l$ is not only the length of a car but the sum of the car length $l_{\text{CAR}}$ and the width of the 1st Fresnel zone $l_{\text{1FR}}$. This length can be named effective car length. According to the maximum detectable speed of a system, sampled at a rate $f_s$, is:

$$v_{\text{max}} = (l_{\text{CAR}} + l_{\text{1FR}}) \cdot f_s$$  \hspace{1cm} (2)

Figure 4 shows a basic model for vehicle detection using radio irregularity. The length of a car and the length of the 1st Fresnel alongside with the sampling rate of ZigBee WSN define the maximum possible velocity for a car to be detected. According to the testing of the used ZigBee XBee Series 2 modules, the maximum sampling rate is equal to 3.6Hz. If the distance between the nodes is 8m, the average length of a car is 4.2m and the 1st Fresnel zone is 1m, the maximum speed detectable by the system is 18.7m/s (67.4km/h). If the proposed system is installed on an open road, where the speed limitation is set to 90km/s, the vehicle detection of this system will fail. In order to enhance the ability to detect vehicles traveling at higher velocities, it is required to widen the 1st Fresnel zone. The method presented in this paper is placing the propagation path in a lower angle to the roadway, seeking to be parallel (Fig. 5.).

![Figure 4. Vehicle detection model](image)

![Figure 5. Enhanced model for vehicle detection](image)

The Fig. 5 shows the enhanced model where the detection zone area is expanded throughout the roadway. By placing the propagation path to an angle from the initial position, the detection length of the propagation path is expanded from the original 1st Fresnel zone. The detection length depends on the node distance in y plane, $b$, and angle $\alpha$.

$$l_{\text{1FR}} = \frac{2}{\lambda b \sin \alpha - 4 (\cos(\alpha))^2} \cdot \frac{b}{\sin \alpha}$$  \hspace{1cm} (3)

Where the $\lambda$ represents the wavelength and $b$ represents the distance from the nodes longitudinal to the road. If the length is graphed versus the angle $\beta$ (which represents the angle between the initial position and current position), the data is shown on Figure 6. The expression was obtained from trigonometric functions and 1st Fresnel zone calculation formula [22].

![Figure 6. Effective length vs. Angle](image)

If the maximum detectable velocity is expressed from (1), the graphic representation of maximum detectable velocity vs. angle is shown in Fig. 7. According to Fig.7, the minimum angle $\beta$ required to enable the detection of vehicles traveling at velocities up to 90km/h is 60°.

![Figure 7. Detection velocity vs. Angle](image)

Another theoretical aspect that has to be taken into consideration is the free space loss and the expected received power in dBm versus the distance of the nodes (angle $\beta$ respectively). According to [22], the amount of loss between receiving and transmitting node is equivalent to free space losses (if no obstacles are present in 60% of 1st Fresnel zone) subtracted by antenna gain. If the maximum transmit power is 2mW (3dBm) and receiver sensitivity is equal to -96dBm [23] then the maximum angle $\beta$ is defined by the induced losses. The projected received power against angle $\beta$ is shown in Fig. 8.

![Figure 8](image)
according to desired vehicle detection velocity. By increasing the angle $\beta$, the width of the Fresnel zone is increasing as well, so the mitigation caused by the pass of the vehicle is reduced. This can present a positive aspect in terms of packet loss; however it can reduce the chances to detect a passing vehicle by means of radio irregularity.

![Figure 8](image_url1)

**Figure 8.** Received Signal Strength (RSSI) vs. Angle

**IV. TESTING OF THE PROPOSED VEHICLE DETECTION METHOD**

In order to test the theoretical aspects stated in Section III, the measurement of the vehicle influence on RSSI value was conducted in three scenarios. The first scenario was set up according to Fig. 4 whereas the two remaining scenarios were set according to Fig. 5 with angles $\beta$ 56.3° and 68.2° respectively. The equipment was set up in a rural environment (near the town Požega, Croatia).

To set up the WSN and detect the RSSI values, ZigBee Digi XBee Series 2 modules were used. In order to acquire the RSSI values, a LabVIEW application was developed to periodically poll the remote ZigBee node. After every poll, the received signal strength was displayed on a graph. The first test included testing the ability to detect a vehicle traveling at low velocity, and the results alongside with the LabVIEW application are shown in Fig. 9.

![Figure 9](image_url2)

**Figure 9.** LabVIEW application displaying a drop in RSSI value

Figure 9 shows a drop in RSSI value upon a vehicle pass (circled in red) by approximately 22dB. This proves the theoretical background presented in Section III and demonstrates the ability to detect a passing vehicle using radio irregularity phenomenon. Also, it is visible that the static RSSI value is located around -51dBm which corresponds with the calculated RSSI value for angle of 0°, according to Figure 8. Furthermore, the end of a graph displays a drop in RSSI value by 5dB, however due to the low gradient value it can be concluded that the drop was not caused by a passing vehicle, but by an unknown fading phenomenon. The gradient parameter can be effectively used in vehicle detection, as the following figures display the RSSI values in time for different vehicle velocities.

![Figure 10](image_url3)

**Figure 10.** RSSI Values for different velocities:

a) 20km/h, b) 40km/h, c) 60km/h, d) 80km/h, e) 100km/h
As seen from Figure 10, the velocity of the vehicle is in direct correlation with the duration of the RSSI value drop and the angle $\beta$. The higher the angle $\beta$ is the wider the RSSI drop is, thus allowing the detection of higher velocities. For the angle $\beta = 0$, after a certain speed the traveling vehicle avoids detection, Fig. 10 d). If the angle is raised the detection is possible for even higher velocities (Fig. 10 d) and e). If the comparison is made between the measured delays translated into effective length, then it is visible that the measured length follows the calculated lengths shown in Fig. 11.

![RSSI Drop time vs. Vehicle velocity](image)

**Figure 11.** RSSI Drop time against vehicle velocity

### V. CONCLUSION AND FUTURE WORK

This paper presents a novel method for vehicle detection in adaptive roadway lighting by the means of radio irregularity. After proposing two basic approaches for adaptive roadway lighting, the idea of vehicle detection using radio irregularity is proposed from a theoretical point of view. From the measurements conducted it can be concluded that the theoretical background proposed for vehicle detection using radio irregularity is valid, giving the proposed method for vehicle detection a practical aspect for implementation. From the measured results it is clearly seen that the pass of a vehicle is evident in drop of RSSI value under a certain gradient. The gradient depends mostly on the vehicle velocity, the angle $\beta$ and in smaller amount on the physical dimensions of a vehicle. In order to detect vehicles traveling at higher velocities, the angle $\beta$ must be set to allow the detection restricted by the sampling rate of WSN nodes. By using WSN nodes with the possibility of higher sample rates, the detection can be enabled for even higher velocities (e.g. highway).

Future work involves implementing a detection system inside a programmable ZigBee or a DigiMesh node (e.g. Digi XBee or DigiMesh modules) in order to enable the detection of vehicles by analyzing RSSI value drop through time. The proposed detection could be based on the gradient analysis or an AI agent to learn and adapt to the RSSI drops, thus enhancing the precision of vehicle detection. Finally, the implementation and testing of the proposed method is recommended alongside with the analysis of vehicle detection accuracy.

### REFERENCES


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