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Mobile Wireless Sensor Networks in a Smart City

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Abstract

This research supports the possibility of implementing in a smart city, a wireless sensor network, with sensitive nodes in movements implemented in public transport system vehicles and static sink nodes located in a vehicular intersection. The methodology contemplates the influence of mobility in obtaining the parameters of network operation, through mathematical models and probabilistic calculations of the data collected through measurement campaigns carried out in a real traffic light intersection. A model is obtained to calculate the probability of success of the communication based on the speed of the sensitive node and the size of the payload.

Keywords

Coverage, discovery time, measurement campaigns, MWSN, network operation parameters, payload.

A Smart City is based on intelligent infrastructures, the connection between man and technology and a growth that respects sustainability, economic Intelligence and Social Inclusion (Caragliu et al., 2011; E. Commission, 2014). The use of Information Technology (IT) in a smart city interconnects its systems and connects the citizen with its environment, allowing the monitoring of the different actors, to understand, analyze, and manage resources efficiently with the purpose of planning a city that improves the quality of life of its inhabitants (Batty et al., 2012; Góngora, 2015).

The use of IT to make an infrastructure or system intelligent implies adding two characteristics to its normal operation: sensing and automation; these are necessary to collect information, process it and perform corrective actions autonomously (Arroub et al., 2016).

Wireless Sensor Networks (WSN) are composed of sensitive nodes (Sensor Nodes) and sink nodes (Sink Nodes). The sink nodes can be integrated into the urban infrastructure with fixed or moving nodes (Jain and Shah, 2016; Yazdi, 2014). The introduction of mobility in the WSN, Mobile Wireless Sensor Networks (MWSN) allow to expand the scope of applications and improve communication due to the versatility of the topologies that can be implemented, but in turn, sensor mobility brings challenges of network deployment and effects on its operation. These challenges and effects vary depending on the type of the application, the connectivity of the network and the nodes that compose it, the variable to be monitored, the location of the sensors, the speed of the sensor, and the topology of the network (Cattani et al., 2011; Chen et al., 2016).

The WSN are framed within the IEEE 802.15.4 standard, which defines the physical layer (Physical Layers, PHY) and the Medium Access Control (MAC) layer of wireless communication systems with low rate data transmission, low power consumption and little complexity in its implementation (IEEE Computer Society, 2011). However, this standard does not include nodes in motion. The technologies that implement MWSN do not have a defined standard, so they base the PHY and MAC layers in IEEE 802.15.4 and the mobility is assumed in the upper layers specific to each technology. Mobility in MWSN networks can appear in three main ways: mobility of the sensor node, sink mobility, and mobility of the event (Karl and Willig, 2006), with mobility being a limiting factor in the deployment of the network in terms area coverage, average duration of the communication, the rate of data transfer and the speed of the mobile node (Agusti et al., 2010).

In scientific literature there are numerous studies dealing with issues related to IEEE 802.15.4 and the MWSN. Some analyze the propagation losses in different environments, the performance and energy consumption of the sensors by means of measured data (Rossi, 1999; Benkič et al., 2008; Pollin et al., 2008; Zen et al., 2008; Cattani et al., 2011; Camargo-ariza et al., 2013; Kabrane et al., 2016; Xiong et al., 2016). Other investigations perform simulated studies about mobility within the standard (Javed et al., 2013; Mouawad et al., 2013; Yang et al., 2013; Gupta and Roy, 2014; Das and Roy, 2015; Kar et al., 2016; Kaur, 2015; Shaukat and Hashim, 2015; Wan et al., 2015; Zhang et al., 2015).

Unlike these studies, the present study shows the mobility analysis of a wireless network with mobile sensitive nodes implemented in the public transport system vehicles, integrating the study of different variables in an urban outdoor environment, specifically in a vehicular intersection controlled by traffic lights where the fixed sink node is located. The variables measured and analyzed in this research are: Received Signal Intensity (RSSI) levels, mobile node speed and discovery and connection times. The data was filtered, processed and modeled in order to obtain the network design parameters for real operating conditions.

This work makes possible a MWSN in a smart city with sensitive nodes placed on public transport. Its principal aim is created a City Sense Cloud (CSC), storing historical environmental variables like as particulate matter of 10 μm or less diameter (PM10), sulfur dioxide (SO_2), nitrogen dioxide (NO_2), ozone (O_3), total suspended particulates (TSPs), carbon monoxide (CO), Particulate Matter of 2.5 μm or less diameter (PM2.5). Additionally, is able to monitoring city vehicular traffic leave aside mobile 3G and 4G network.

Methodology

This is a fundamental, explanatory, and quantitative research that aims to establish design parameters and operating conditions of a wireless network of mobile sensors, which could support future teleservices in a smart city.

The research shows the influence of mobility on the dependent variables that determine the deployment of the network, through mathematical models and probabilistic calculations of the data collected through measurement campaigns.

The test scenario consists of a cell containing a base station consisting of an XBee Series 2 PRO sink node, model XBP24-B from the manufacturer Digi International with a unit gain omnidirectional antenna at a height of 4 m and a laptop connected to the Internet. The mobile nodes are the buses of the city's transport system, which at the top are equipped with a Rasberri Pi model 3B computer with the sensors and an XBee

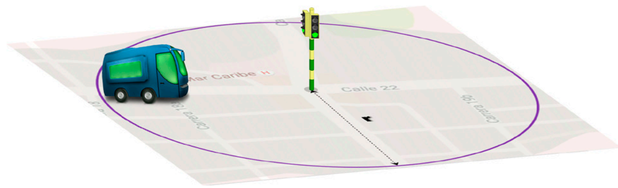

Figure1: Test scenario.

XBP24-B transmitter with an omnidirectional antenna of unity gain to an average height of 3 m as illustrated in Figure 1. The radios work at an operating frequency of 2.4 GHz with a power of 3 dBm and a Radio Frequency Data Rate of 250,000 bps and connect to PCs with serial interfaces configured to 9600 bits/s.

Three studies were carried out: coverage, discovery, and connection times, and mobility as a limiting element in the deployment. For each of these, a point-multipoint network is implemented, assigning the roles of the devices as.

Coordinator for the fixed node sink and End Device for the mobile nodes.

Coverage area study

For this study, the RSSI is measured in the XBee modules using the Range Test tool of the X-CTU software, with distance as the independent variable. Measurements are made every 20 meters, starting with $r_0 = 1$ m until the RSSI decreases to values close to the sensitivity of the experimentally found receiver (−88 dBm), taking 10 measurements for each point.

From the RSSI the propagation losses are calculated by

$$P_R = P_T + G_T + G_R - L, \qquad (1)$$

where P_R is the RSSI in the receiver, P_T is the intensity of the transmitted signal (3 dBm), G_T and G_R are the gains of the antennas of the transmitter and receiver, and by being unitary they have a value of 0 dB, and L are the propagation losses in the environment, described by

$$L = k + 10n\mathrm{Log}\left(\frac{r}{r_0}\right). \qquad (2)$$

Being K the average attenuation of the channel, r_0 it is a reference distance for far field and is the exponent of loss. Through the logarithmic transformation of the independent variable r by $\log\frac{r}{r_0}$, the equation is linearized, and using the least squares fitting technique, we obtain the intersection and the slope of the line that models the propagation losses depending on the distance.

To determine the quality of the alignment, the sample determination coefficient R^2 and the homoscedasticity of the model are evaluated with the Levene Test. If the model adjusts, the residuals are examined evaluating that they follow a normal distribution with zero mean, using the Shapiro–Wilk and Kolmogorov–Smirnov tests with the Lillie for correction (Guisande González et al., 2011).

After validating the model, the radius of coverage of the cell is estimated from Eq. (3),

$$r = 10^{\left(\frac{L_{max} - k - \varphi_{[dB]}}{10n}\right)} \times r_0, \tag{3}$$

where L_{max} are the maximum allowed losses to obtain an RSSI equal to the sensitivity of the receiver, and φ (dB) is the relative loss gain for an interruption probability of 1%, following the Gaussian distribution (Goldsmith, 2005). This value is calculated from

$$\mathrm{Prob}(\varphi_{dB}) = \int \frac{1}{\sigma_{\varphi_{dB}}\sqrt{2\pi}} e - \frac{(\varphi_{dB} - \mu_{\varphi_{dB}})^2}{2\sigma^2_{\varphi_{dB}}} d\varphi_{dB}, \tag{4}$$

where $\mu_{\varphi_{dB}}$ is equal to zero and $\sigma_{\varphi_{[dB]}}$ is the mean square error of the model obtained.

Discovery and connection times

The connection time τ is estimated as the sum of the discovery time t_{des}, and the transmission time, t_{com}. The t_{des} is the time it takes for the devices to pair and exchange control frames to start transmitting useful information. The t_{com} is the time required to send the payload once the devices are paired, this approximates the time used in the serial interface, t_{RS}, time that depends on the sent bits and the speed of the serial interface (9600 bits/s). The times elapsed in the MAC and PHY layers are neglected because they are very small compared to t_{des} and t_{RS}. Thus, it is possible to calculate the connection time by

$$\tau = t_{des} + t_{RS} \tag{5}$$

The average time that a communication lasts, *D*, for a fixed payload can be modeled as the average of the random variable τ, which comes from an exponential distribution. Since the randomness of τ depends on t_{des}, it is verified that t_{des} follows an exponential distribution and its average is calculated.

In this study, 100 measurements are taken to find the discovery time t_{des} from the difference between the instant in which the communication begins and the moment in which the mobile node enters the coverage area of the sink node. This study is done in a controlled environment in the laboratory.

To measure discovery time a Faraday cage was implemented. this shield obstructs the receiver while transmitter is active. After that, the receiver is expose and we measure the time until communication has been established.

Since t_{des} is never zero, the transformation of the variable is performed, using the difference between the discovery time measured in all tests t_{des} and the minimum measured discovery time found, $t_{des_{min}}$. Subsequently, it is verified that this variable has a behavior of an exponential distribution, according to Eq. (6), (Bernardo et al., 2010; Gomez et al., 2018). For this, the Kolgomorov–Smirnoff test and Log Verisimilitude are used:

$$f\left(t_{des} - t_{des_{min}}\right) = \lambda e^{-\lambda\left(t_{des} - t_{des_{min}}\right)} \tag{6}$$

If the times $t_{des} - t_{des_{min}}$ are adjusted to the exponential distribution, the mean discovery time $\overline{t_{des}}$ is estimated, which is the random average of t_{des}, from the expected value of the exponential distribution λ and the $t_{des_{min}}$, using Eq. (7).

$$\overline{t_{des}} = \frac{1}{\lambda} + t_{des_{min}}. \tag{7}$$

Consequently, the average time a communication lasts, *D*, approaches:

$$D = \overline{t_{des}} + \frac{\text{Payload}}{9600} \tag{8}$$

Additionally, the time that 50 city buses of the public transport system take in crossing the cell with radio at the intersection of the test scenario in its usual route is measured, (N–W, W–E, W–N, N–S, N–E, S–N, E–W, E–N).

Influence of mobility

The purpose of this study is to validate the success of the transfer of information to the sink node by the sensor node that is in motion, assuming mobility as the limiting element of network deployment.

For this, the probability that the mobile sensor node requires another cell to transmit the information using the probability of a P_h handover occurrence is evaluated. P_h is calculated according to Eq (9), considering that the base station is in the center of the cell (the intersection traffic light), that the mobile node crosses the cell in the interval [0, 2*r*] at a constant speed, *v*, and at a time *t*, and that *D* is the communication time average of the random variable τ, which comes from an exponential distribution (Agusti et al., 2010).

$$P_h = \int_0^{2r/v} e^{-t/D} \frac{1}{2r/v} dt = \frac{v \times D}{2r}\left[1 - e^{-2r/v \times D}\right]. \quad (9)$$

The probability that the mobile sensor node cannot deliver the information to the sink node increases when the coverage radius decreases, the speed of the mobile node increases and/or the average duration of the communications increases.

The probability of successful transmission in the cell is defined by

$$P_{sucess} = 1 - P_H. \quad (10)$$

In addition, in the test cell the speed with which the sensor node passes through the cell is varied, with increments of 5 km/h until reaching the city speed limit allowed (60 km/h). At each of the speeds, a payload of variable size test was sent, from 80 bytes and increasing it until the information cannot be delivered at this speed.

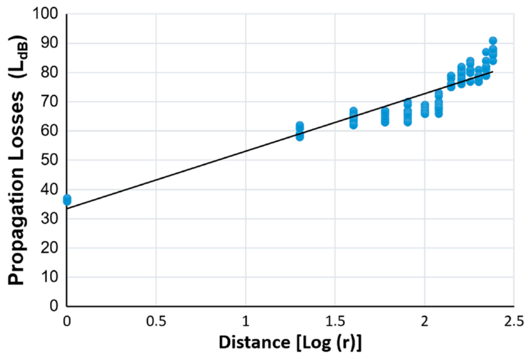

Figure 2: Path loss.

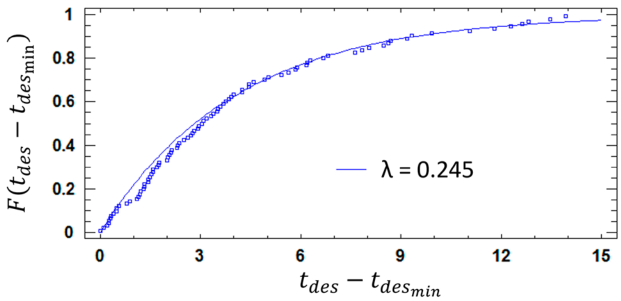

Figure 3: Function of the cumulative exponential distribution.

Results

The most relevant results of applying the previous methodology that also allow obtaining the conclusions of the investigation are shown below.

Table 1. Payload depending on the times found.

		Time taken by buses to cross the cell = *D*		
		$D_{min} = 31\,s$	$\bar{D} = 145{,}17\,s$	$D_{max} = 309\,s$
Discovery time	$\overline{t_{des_{min}}} = 4{,}087\,s$	Payload = 258.364 bits	Payload = 1.354.396 bits	Payload = 2.927.164 bits
	$\overline{t_{des}} = 8{,}1686\,s$	Payload = 219.181 bits	Payload = 1.315.213 bits	Payload = 2.887.981 bits
	$t_{des_{max}} = 18{,}024\,s$	Payload = 124.569 bits	Payload = 1.220.601 bits	Payload = 2.793.369 bits

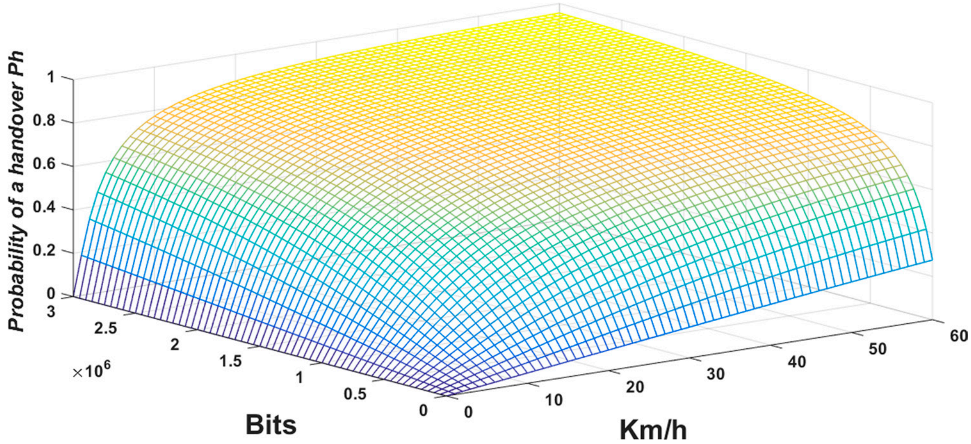

Figure 4: Probability that the mobile sensor node requires another cell.

Cell radius

The loss model for the traffic light intersection is shown in Eqn. (11), and can be seen in Figure 2.

$$L_{dB} = 32.7621+10\,(2.17629)\log_{10}(r) \quad (11)$$

The model presents an $R^2=0.944978$, and has homoscedasticity tested with the Levene Test with a parameter equal to 0.200783. Additionally, it has a deviation of $\sigma\_\varphi=4.01296$ dB, and the residuals follow a normal distribution corroborated with the Shapiro–Wilk tests (SW = 0.938791) and Kolmogorov–Smirnov with the Lilliefor correction (KS = 0.498097).

Using σ_φ we find the relative losses, φ, and the coverage radius, using Eqs. (4) and (3).

The coverage radius of the sink node located at the traffic light intersection, obtained from the model and the relative losses, $\varphi = 6{,}44$ dB, for an interruption probability of 1%, is $r = 240$ m.

Discovery and connection time

The discovery time obtained in the 100 measurements varied between 4,087 and 18,024 s.

We show that $t_{des} - t_{des_{min}}$ is a random variable that follows an exponential distribution described in Eq (6), tested with the Kolgomorov–Smirnoff test (0.0867753) and Log Verisimilitude (–214.105), as can be seen in the cumulative probability function observed in Figure 3. This distribution has a $\lambda = 0.245$.

The average duration of discovery time $\overline{t_{des}}$ is estimated using Eq. (7) and generating $\overline{t_{des}} = 8.1686$ s as a result.

The time that the buses spend crossing the cell, $2r = 480$ m, in their usual route varies between 31 and 309 s, with an average equal to 145.7 s, and the average speed of the buses inside the cell is 14,1797 km/h.

The optimal payload sizes to be transmitted could be obtained by matching the time it takes for buses to cross the cell with the average connection time.

Next, Table 1 relates the most significant t_{des} and D with the possible payload sizes. Using (8) the payload is calculated, where D is a minimum, medium, and maximum time that the bus used to cross the cell. Discovery time measured (minimum,

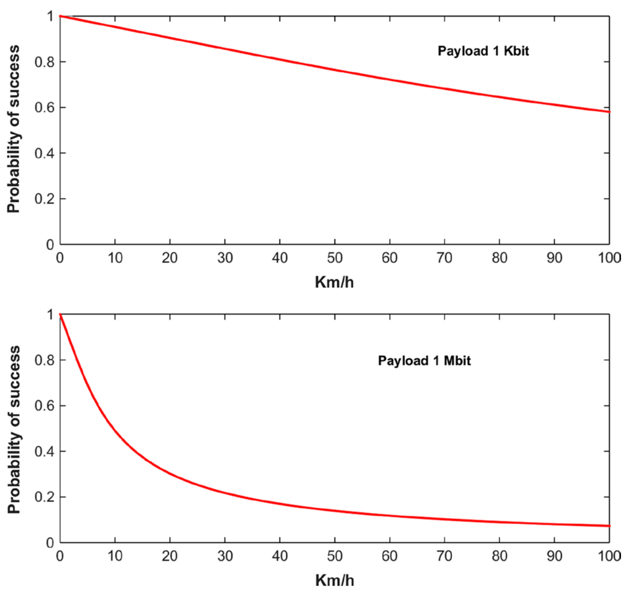

Figure 5: Probability of success in transmission depending on speed.

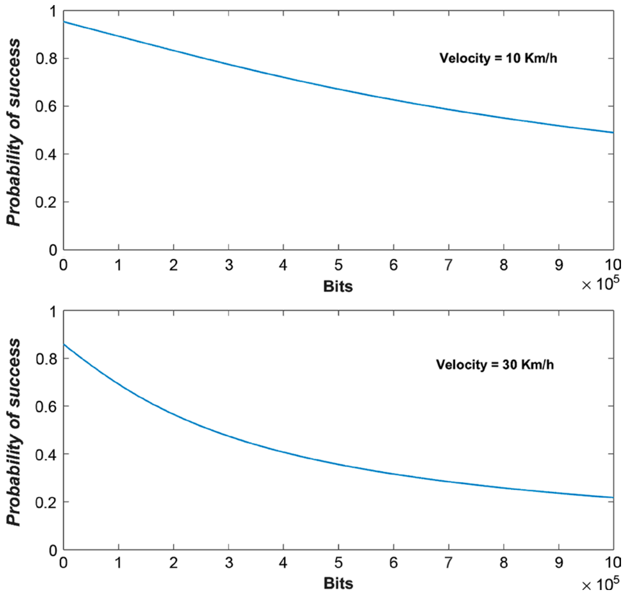

Figure 6: Probability of success in the transmission depending on the payload.

medium and maximum) is show in Table 1. According to the times found, the payload size can vary from 124,569 bit to 2,927,164 bit.

Influence of mobility

The probability that the mobile sensor node requires another cell to transmit the whole message to the sink node according to Eq (9) is plotted. For this, the radius of the cell $r = 240$ m, found for an interruption probability of 1%, is used, and the velocity of the mobile node and the payload are varied; the average duration of the connection is calculated according to Eq. (8), with a discovery time $\overline{t_{des}} = 8.1686$. This is shown in Figure 4.

In addition, the probability of success in the transmission is plotted depending on the speed of the sensor node, for different payloads, shown in Figure 5 and the probability of success in the transmission and depending of the payload for different speeds, as shown in Figure 6.

In the test cell and experimentally, this analysis was validated, finding that the information can always be delivered successfully when it meets the speed relationships and the size of payload size show a handover probability P_h, according to Eq (8), less than 0.1. As shown in Figure 7.

This study can be extended by a bio-inspired algorithm. In a probable future extension, the algorithm implemented into electronic system to guarantee a transmit successful while the bus cross the cell. This algorithm calculate the optimal payload based to vehicular traffic of the city.

Conclusions

It is possible to implement an MWSN, with moving sensing nodes located in the transport system, and static sink nodes located at the traffic lights; as long as the payload size to be delivered to the sink node is adjusted to the coverage radius of the cell and to the speed of the sensor node, to guarantee a 0.9 as set out in (10).

The probability that the mobile sensor node cannot deliver the information to the sink node increases when the coverage radius decreases, the speed of the mobile node increases and payloadincreases. If the radius of the cell is taken as reference as 240 m, the average speed of the bus in the cell of 14.1 km/h and the mean of the discovery time found is 8.16 s; and the range of 0.9 is maintained for the probability of success, the size of the suggested payload is 38kb.

The coverage radius of the cell is a design parameter that cannot be changed after implementing the network without changing the equipment, the speed of the sensor node depends on the state of the traffic

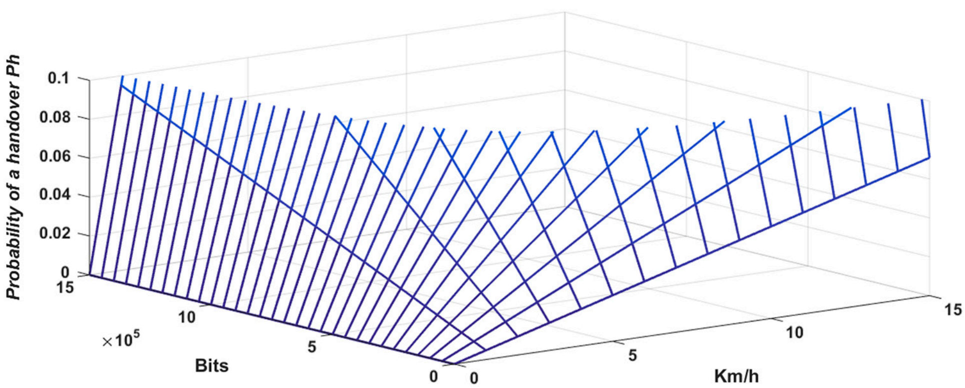

Figure 7: Probability that the mobile sensor node requires another cell.

and it is difficult to control, but the payload is a variable that can be manipulated to obtain a successful communication in the cell.

In the test cell and city, it was found that the average speed of the transport system at the traffic light intersection has a large range of variation, from 5.3 km/h to 53.41 km/h. This variation is largely due to the state of the traffic light and time of day; for this reason, it is not recommended that the size of the payload be static, but that it is intelligently adjusted to the average speed with which the bus travels.

The mathematical models proposed in the studies of the coverage area, connection time, and influence of mobility manage to describe the behavior of networks based on the IEEE standard 802.15.4, finding clear operating conditions for this type of network that can be extrapolated.

The results obtained agree with the state of the art about mobility based on IEEE 802.15.4. Javed et al. (2013) and Zen et al. (2008) reported problems with the times to deliver the load, energy, and environmental effects. The results obtained in this work are adjusted to those proposed by Yang et al. (2013) in simulated environments, which shows that the better performance for the mobile node is obtained at 10 m/s.

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