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# A Delay-Aware Coverage Metric for Bus-Based Sensor Networks

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## Abstract

Embedding sensors in urban buses is a promising strategy to deploy city-wide wireless sensor networks. By taking advantage of the mobility of buses, it is possible to achieve extended spatial coverage with fewer sensors as compared to a static setup. The trade-offs are that urban buses only cover part of the city, and that the frequency of the buses, and consequently of the data collection, is inhomogeneous across the city. Depending on the communication technology, buses may be unable to deliver the collected data on time. In this paper, we propose a coverage metric that takes into account the delivery delays of sensed data and the frequency at which a given region is sensed. The metric indicates, for a given time window, the proportion of streets that can be sensed under the requirements of an application. We apply the metric to more than 19 million GPS coordinates of 5,706 buses in Rio de Janeiro, mapping the coverage achieved for different application needs during a week. We build an abacus relating the coverage to different application requirements. We also calculate the coverage of a scenario only with static sensors. We show, among several observations, that bus-based sensing increases the coverage of applications by up to 7.6 times, in the worst case analyzed, when compared to a pure static scenario.

*Keywords:* Vehicular sensing, Internet of Things, Wireless Sensor Networks

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## 1. Introduction

A clear advantage of mobile wireless sensor networks (MWSN) is that they can use mobility to expand the coverage area of a smart city [1]. When compared to static sensors, the deployment of mobile sensors involves two main challenges. Firstly, communication links between nodes and gateways are intermittent. Therefore, sensors must store sensed data until there is a connection to a gateway, delaying the transmission and delivery of sensed data. The second challenge concerns the measurement frequency. As zones of the target area are covered only when a mobile sensor passes nearby, intervals between readings are inherently heterogeneous.

The communication delay and the measurement frequency determine whether a specific application may run on top of the MWSN. In this paper, we consider the case where mobile sensors are embedded in urban buses. Even though buses connected to the cellular network could probably deliver gathered data with negligible delay, recent offloading concerns show that it is important to unload the cellular networks using secondary infrastructures [2]. In this case, buses could leverage the existing offloading infrastructure to deliver delay-tolerant data. We consider that gateways are placed in bus stops. The delivery delay depends on the itinerary of bus lines, the traffic conditions, and the location of bus stops.

Previous studies have considered the coverage of MWSNs. Liu *et al.* [1] and Ekici *et al.* [3] investigate the effects of mobility on coverage and on data delivery. Mosaic [4, 5, 6] and Opensense [7] projects show the feasibility of such networks for air quality applications, using machine learning techniques to predict missing data. The works from Ali *et al.* and Cruz *et al.* [8, 9] propose a coverage metric for bus-based WSNs, but do not take into account the delays generated by the mobile coverage and transmission. The work from Zhao *et al.* [10, 11] characterizes opportunistic coverage, proposing a metric called Inter-Cover Time, but does not take into account delays in data delivery.

We propose a coverage metric that takes into account the delivery delay and the measurement frequency of a given street section. Since applications have

different requirements of data delivery delay and measurement frequency, the metric considers that buses can cover a street section if and only if they gather data with a *minimum measurement frequency* and deliver the gathered data with a *maximum delivery delay*. We apply the metric to real mobility traces  
35 of buses from the city of Rio de Janeiro. We present the results in the form of an abacus, relating coverage to different tolerances in terms of delivery delay and measurement frequency. We map the coverage obtained by buses to the applications of waste management, air quality monitoring, and noise monitoring. We also compare the coverage obtained to the scenario where bus stops serve  
40 as gateways to static sensors. Taking the application of waste management as an example, our results show that buses can cover up to 16.4 times the region that it would cover with static sensors. This value corresponds to a coverage of 27.9% of the streets of Rio de Janeiro.

The main contributions of the paper can be summarized as:

- 45 • We propose a coverage metric that takes into account the delivery delay and measurement frequency required by applications.
- We measure the achievable coverage provided by a MWSN using bus traces collected in Rio de Janeiro.
- We compare the coverage obtained by a bus-based mobile WSN and a  
50 static WSN, for different applications.

This paper is organized as follows. In Section 2, we position this paper in relation to the scientific literature. Section 3 describes the scenario of bus-based urban sensing. In Section 4, we propose a coverage metric designed to deal with the delays and sensing frequencies of the studied scenario. In Section 5, we  
55 apply the metric to real mobility traces of buses of the city of Rio de Janeiro. Section 6 concludes the work and points out directions for future work.

## 2. Related work

The literature presents some works in bus-based MWSNs and more generally, vehicle-based WSNs. It is possible to note that coverage is an important  
60 measure of the effectiveness of a WSN. There are still open challenges to the characterization of coverage, depending on the application.

### 2.1. Vehicle-based urban sensing

Vehicle-based urban sensing is a relevant option to collect data for smart cities applications. The following works present different strategies to better  
65 adequate the data collection and delivery to the mobile scenario. The metric proposed in this paper could be used by these works to estimate the covered area by each one of them or as a comparison with each proposal and other alternatives.

The pioneer project BusNet [12] monitors road surface condition using sensors embarked in buses. Buses are used as data mules, taking raw data from  
70 a secondary station to another one until data reaches the main station. Once in the main station, the information about the road condition is retrieved and served to final users.

Projects Mosaic [4, 5, 6] and Opensense [7] use urban buses to monitor the  
75 air quality of cities. Since pollution sensors are not reliable in the presence of mobility, Mosaic designs an algorithm to improve the accuracy of pollution sensors in a mobile scenario. Opensense proposes log-linear models to infer the air quality of uncovered regions. In Mosaic and Opensense, buses are connected all the time with the cloud, being able to send data with negligible delay.

80 Alsina *et al.* [13] design a bus-based WSN for noise monitoring. The paper evaluates the costs and equipment requirements to implement this network. They also propose strategies to build a noise map of the city canceling the noise from the bus carrying the sensors. The authors conclude that the application of noise monitoring can exploit the mobility of urban buses to improve its coverage,  
85 an assumption we share with them.

The work of Apte *et al.* and the work of Von Fischer *et al.* both explore the predictable mobility of Google Street View cars. Apte *et al.* embark sensors in the cars to measure the air quality in the city of Oakland [14], proposing methods to implement similar services in other cities. Similarly to this work,  
90 Apte *et al.* uses street sections of the city to define the regions of the city that can be covered. Von Fischer *et al.* use the improved coverage provided by Google Street View cars to detect gas leaks and rapidly communicate them to maintenance teams, avoiding accidents [15]. To infer the magnitude of the gas leaks, the measurements obtained by sensors and the speed of the wind are used  
95 by a prediction algorithm.

SmartSantander uses vehicles as part of a multi-purpose WSN to gather data about the city of Santander [16]. Other urban objects are used to sense and actuate in the city, providing services to its citizens. The work presents a framework to integrate IoT in the smart city environment and deploys a city-  
100 wide network, showing the feasibility of this system and some applications that can benefit from it, such as environmental monitoring and smart parking. In the communication paradigm used, data is delivered immediately to the applications. This means that there is no concern about delivery delays, but there is also no benefit from offloading infrastructures.

SensingBus [17] uses a three-level architecture to collect, transmit and serve  
105 data on a smart city. Sensing nodes, embarked in buses, gather data from the city; fog nodes coupled to bus stops receive and pre-process raw data from buses, sending it over the Internet to the next level; the cloud level processes and serves data to users. Hence, SensingBus explores delay-tolerant communication.  
110 In another work, the authors propose a model for the delays and a selection algorithm to choose bus stops to place fog nodes minimizing the delivery delay respecting budget constraints [18]. The present work is in the same context of SensingBus, and has as main objective to discover the coverage provided by systems similar to SensingBus.

115 The works listed can apply the metric proposed in the present paper to define a notion of coverage for these works. The metric reveals which regions of the

city can benefit from the applications offered by each of these systems.

## 2.2. Mobile wireless sensor networks coverage

The coverage of MWSNs gives an important indication of the quality of data  
120 generated by these networks [19]. Mosaic and Opensense use different strategies  
to study the coverage of their proposals. Mosaic divides the city using a grid and  
sets a score for every grid cell, depending on the number of routes that include  
the grid cell [6]. Additionally, Mosaic proposes an algorithm to select the best  
buses to receive sensing nodes and cover points of interest spread in the city.  
125 Opensense [7] divides the city into street segments and uses log-linear models  
to predict pollution data on segments that could not be directly measured. The  
results obtained by Opensense show that, for urban environments, the street  
segmentation is more appropriate than grid partitioning. The metric proposed  
in the present paper uses street segmentation and enables the estimation of  
130 the coverage of Opensense and Mosaic by taking into account the number of  
measurements in each street segment. This makes possible to identify places  
where, even though there are a few measurements, they are not enough to  
serve as input to the applications. Neither Mosaic nor Opensense consider the  
data delivery delay. For this reason, their coverage models are not suited for  
135 opportunistic delivery.

Ali and Dyo propose a coverage metric for a bus-based WSN focused on  
road surface inspection [8]. Their proposed metric divides the city into street  
segments and considers a street segment as covered if at least one bus line passes  
through it. Ali and Dyo also propose a method to choose a limited number of bus  
140 lines while maximizing coverage. The authors test the method using a dataset  
containing the routes of London buses. In our previous work, we propose a  
similar approach, but we consider the lengths of the streets when calculating  
the coverage [9]. The basic idea of this metric is that longer streets produce  
more data. We also propose a method to maximize coverage when the number  
145 of buses that can be part of the network is limited. We apply the method to GPS  
traces of the city of Rio de Janeiro and obtain the maximum possible coverage for

different budgets, in terms of the number of participating buses. Nevertheless, our previous work does not take into account the delays caused by intermittent connection or application requirements in terms of measurement frequency. The  
150 present work proposes a more general metric, that considers both delays and measurement frequency when calculating the coverage. These works can be interpreted as particular cases of the present work. Our previous work is a case where applications need only one measurement per street segment, disregarding the delivery delay. The work by Ali and Dyo is a specific case of our previous  
155 work, where all streets have unitary length. Consequently, the work by Ali and Dyo is a specific case of the present work, that needs only one measurement, has no delay restrictions and every street segment has unitary length

Zhao *et al.* propose a coverage metric for vehicle-based WSNs that takes into account the time between measurements [10, 11]. In their work, time is  
160 discretized into slots and the area of the city is divided into a grid. A cell in the grid is covered for a given time slot if and only if a participating vehicle is inside the grid cell during the time slot. They also propose a metric called Inter-Cover Time, which is the time elapsed between two consecutive samples of the same grid cell. They also propose a metric called the opportunistic coverage ratio,  
165 which is the expected number of covered grid cells on a given time interval. In our work, we use the measurement frequency to determine whether there is enough information in time, taking advantage of the predictability of buses routes. Additionally, we add the delivery delay to our coverage metric, making sure that applications get data in a timely manner. Zhao *et al.* do not consider  
170 the delivery delay in their metric.

The work by Zhang *et al.* introduces a coverage metric for Mobile Crowd-sensing Networks [20]. In their metric, points of interest (POI) are sensed if a participating user is within the sensing range of the POI. Since POIs are weighted according to their importance, the total coverage is the sum of weights  
175 of the union of all sensed POIs. Crowdsensing coverage is also explored by Chon *et al.* [21]. They consider a place is covered if it is visited by at least one participant in the sensing tasks. Both works do not take into account the



measurement frequency nor the delivery delay of data, making them suited only for applications with no constraints regarding these parameters.

180 Masutani [22] proposes a route control method to maximize the coverage of vehicle crowdsensing. In his work, he uses a coverage metric based on sensing demands. It considers a certain area covered if it is visited by at least one car during a given time window. The time window is the time the sensing task is valid. Masutani ignores the frequency of measurement and the delivery delay  
185 of data. Therefore, his work is not able to predict the coverage of applications that are constrained in terms of these dimensions.

Table 1 shows the main aspects of the work related to MWSN coverage. It shows that the present work, to the best of our knowledge, is the only that proposes a coverage notion considering the measurement frequency and the delivery  
190 delay of sensed data. This makes the proposed metric capable of estimating the coverage of a larger number of applications, since it considers their restrictions.

### 3. Bus-based urban sensing: Goals and assumptions

There is a wide range of applications that can benefit from data gathered by buses. A few examples are the applications of pothole detection, air qual-  
195 ity monitoring, and noise monitoring. Some of them also serve as data mules for sensors in buildings, electricity meters, smart lamps, smart trashcans, and others. For such applications to work properly, it is important that data meets certain requirements. In the case of a MWSN with delay-tolerant data delivery, the critical requirements are related to temporal adequacy of data [19]. In this  
200 context, temporal adequacy refers to the sensing frequency of each area, and the time it takes since a bus collects the data until data is available to applications and users. The survey conducted by Zanella *et al.* [23] identifies applications, the frequency of measurement needed, and the delay tolerated by those applications. Sinaeepourfard *et al.* [24] also provide the frequency of measurement  
205 needed for some smart city applications, but gives no information on delays. Table 2 lists applications and its data requirements, according to these studies.

Table 1: Related work and their approach on sensing coverage.

Reference	Considers measurement frequency	Considers delivery delay	Covered unit	Multi-purpose
[6]	Yes	No	Grid tile	No
[7]	Yes	No	Street segment	No
[8]	No	No	Unweighted street segment	No
[9]	No	No	Street segment	Yes
[11, 10]	Yes	No	Grid tile	No
[20]	No	No	Point of interest	No
[21]	Yes	No	Place	Yes
[22]	No	No	Place	Yes
Present paper	Yes	Yes	Street segment	Yes

Table 2: Smart city applications and their data needs in terms of minimum measurement frequency and maximum tolerated delay.

Application	Measurement frequency ( $day^{-1}$ )	Tolerated delay (s)	Source
Waste management	24	1,800	[23]
Air quality monitoring	48	300	[23]
Noise monitoring	144	300	[23]
Electricity meter	96	not defined	[24]
Gas meter	96	not defined	[24]
Temperature	96	not defined	[24]
Weather	48	not defined	[24]

Due to the large amount of data exchanged by users, cellular networks are reaching their operational limits. As pointed by Zhou *et al.*, data offloading through opportunistic mobile networks is one of the main strategies to circumvent this problem [2]. In this strategy, delay-tolerant data is piggybacked on mobile nodes and delivered to gateways in their paths, instead of using traditional cellular networks [25]. In the literature, there are works that propose leveraging the mobility of buses to offload data from the cellular networks [12, 2, 26]. In this case, buses serve as data mules and offload data using gateways spread around the city. Buses carrying sensors can use the same gateways to deliver data collected throughout their paths. Another advantage of using opportunistic communication is to still be able to sense regions not covered by cellular networks, a situation that still happens in some cities.

We assume that sensors carried by buses gather data about the city and store them until a connection with a gateway is possible. We assume that all stored data can be delivered in a single connection. Gateways, located at bus stops, receive data when buses are within communication range, and use the Internet to send this data to a cloud server. The server processes the data and makes it available to applications. We approximate the time that data remains stored in the sensing node by the time a bus takes to travel between two consecutive bus stops. The time for data to travel over the Internet is negligible when compared to the time buses take to travel between bus stops. In this regard, we consider that the delivery delay is the time since data was acquired until it is delivered to a gateway. The paths followed by buses are often cyclic, therefore, the same bus may visit the same location several times a day. In addition, bus lines have overlapping sections and a certain number of trips per day, meaning that different buses may pass by the same location several times a day. Therefore, we define the measurement frequency as the number of times a certain section is measured, considering that data is delivered on time.

As Table 2 shows, different applications have different requirements of measurement frequency and maximum delivery delay. We can notice that the application of waste management tolerates a delay up to 6 times the delay tolerated

by the applications of air quality monitoring and noise monitoring. This is due to the fact that the conditions of waste management infrastructure change more slowly than the conditions of the air quality and the noise in a city.

In a bus-based MWSN with delay-tolerant data delivery, different regions of the city are not sensed with the same frequency. Additionally, their information suffers different delivery delays. This means that not all applications can benefit from data gathered in the same region of a city. Therefore, it is important to use a coverage metric to reflect these requirements. The next section proposes a coverage metric that is aware of delays and frequency measurements.

#### 4. Delay-aware coverage metric

A common way of representing the road map of a city consists of modelling it as a directed graph  $\mathcal{G} = \{\mathcal{V}, \mathcal{E}\}$ . The set  $\mathcal{V}$  contains the vertices of  $\mathcal{G}$ . Each vertex  $x_1, \dots, x_{|\mathcal{V}|} \in \mathcal{V}$  represents an intersection, a curve or other point of interest in the topology of the streets. The set  $\mathcal{E}$  contains the edges of  $\mathcal{G}$ . An edge  $(x_i, x_j) \in \mathcal{E}$  exists if and only if it is possible to follow a street from  $x_i$  to  $x_j$ , not visiting any other vertex. A weight  $l_{(x_i, x_j)}$  is associated to each edge  $(x_i, x_j)$ , representing the distance between  $x_i$  and  $x_j$ . Since a street is an ordered collection of points of interest, a street is a sequence of vertices. A vertex can be part of more than one street, when this vertex is an intersection between two or more streets. The notations used in this paper can be found in Table 3.

In this paper, we use the edges of  $\mathcal{G}$  to represent the street segments of the city. The street segments are used as an atomic unit of the measured region. The concept of a street segment is used in our previous work [9], while similar concepts are used by Ali and Dyo [8] and by the project Opensense [7].

##### 4.1. Opportunistic sensing and data delivery

Each bus in set  $\mathcal{B}$  follows a fixed path through the street segments of the city. The path  $P_b$  of a bus  $b$  can be represented as a sequence of the edges in the graph  $\mathcal{G}$ ,  $((x_i, x_j), (x_j, x_k), (x_k, x_l) \dots)$ , where  $P_b[n]$  is the  $n^{th}$  edge reached

Table 3: Notations used in this work.

Notation	Description	Type
$\mathcal{E}$	Street segments of the city	Set
$\mathcal{V}$	Vertices of the map of the city	Set
$\mathcal{G}$	Graph representing the road map of a city	Graph
$\mathcal{B}$	Urban buses that serve a city	Set
$\mathcal{P}$	The set containing all the paths of the buses of a city	Set
$(x_i, x_j)$	The street segment that starts in vertex $x_i$ and ends in vertex $x_j$	Parameter
$l_{(x_i, x_j)}$	The length of street segment $(x_i, x_j)$	Parameter
$P_b$	The path $((x_i, x_j), (x_j, x_k), (x_k, x_l) \dots)$ of bus $b$ , in terms of edges in $\mathcal{E}$	Sequence
$P_b[m]$	The $m^{\text{th}}$ edge visited by bus $b \in \mathcal{B}$ in its path $P_b$	Parameter
$D_{\max}$	The maximum tolerated delivery delay for the considered application	Parameter
$F_{\min}$	The minimum measurement frequency required by the considered application	Parameter
$v_{(x_i, x_j)}^T$	The number of visits received by street segment $(x_i, x_j)$ on a given time interval	Parameter
$F_{(x_i, x_j)}$	The frequency at which the street segment $(x_i, x_j)$ is visited	Parameter
$\mathcal{E}_c$	The subset of $\mathcal{E}$ that is covered for the considered application	Parameter

by  $b$ . While passing through a street segment, a bus gathers data and stores it until the bus reaches the next gateway. When a connection is achieved, the bus delivers the data. The delivery delay of data gathered in street segment  $(x_j, x_k)$  is the time elapsed between the instant when the first data about this street segment is collected until the instant when data is delivered to a gateway. Figure 1 illustrates this situation<sup>1</sup>. The path of bus  $b \in \mathcal{B}$  is a sequence of vertices that includes street segment  $(x_j, x_k) \in \mathcal{E}$ . Later, when passing by the vertex  $x_l \in \mathcal{V}$ ,  $b$  delivers data to gateway  $g_2$ . The time elapsed between the moment  $b$  reaches  $x_j$  and  $x_l$  represents the delivery delay suffered by the data collected by  $b$  in  $(x_j, x_k)$ . The bus  $b$  also collects data from the street segment  $(x_k, x_l)$  and delivers this data when it reaches  $x_l$ . The delay this data suffers is the time elapsed between  $x_k$  and  $x_l$ .

<sup>1</sup>Shuttle icon made by Skyclick and antenna icon made by Freepik from <https://www.flaticon.com/>. Licensed by Creative Commons BY 3.0

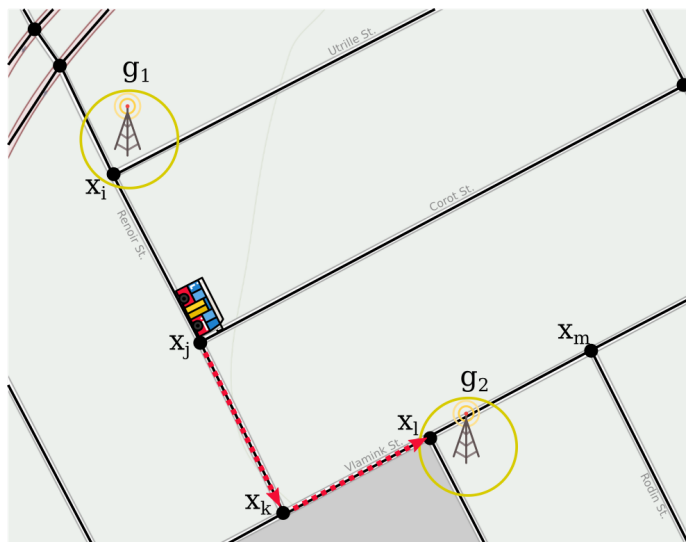


Figure 1: Path of bus  $b$  through the segment  $(x_j, x_k)$  and subsequent delivery in  $x_l$ .

Several variables might influence the delivery delay of data collected in a street segment  $(x_i, x_j)$ . Among them, the traffic conditions, the number of  
 280 times a bus stops to serve passengers, and the distance between  $(x_i, x_j)$  and the gateway where data from  $(x_i, x_j)$  is delivered. As shown in Table 2, different applications can tolerate different data delivery delays. This means that, depending on the delivery delay, data collected on section  $(x_i, x_j)$  may be useful or not for a given application. Since different applications may have different  
 285 tolerances to delay, the same data may be useful to some applications and not for others.

Buses might sense a street segment  $(x_i, x_j)$  several times during a given interval of time  $T$ . This can happen either because  $(x_i, x_j)$  is in the path of more than one bus but also because some buses can pass over the same street  
 290 segment several times during  $T$ . In this case, it is possible to say that there is a certain measurement frequency of street segment  $(x_i, x_j)$ . As shown in Table 2, applications might need a certain measurement frequency to provide a reasonable service to its users.

#### 4.2. A delay-aware coverage metric

295 It is important that a coverage metric reflects application requirements in terms of delays and measurement frequency. To define the coverage for a given application, we use its maximum tolerated delay,  $D_{\max}$ , and its minimum tolerated measurement frequency,  $F_{\min}$ . We say that a bus  $b \in \mathcal{B}$  has visited street segment  $(x_i, x_j) \in \mathcal{E}$  if, after passing by  $(x_i, x_j)$  and collecting data,  $b$  is able to  
300 deliver the data before  $D_{\max}$ . We can define the visiting frequency  $F_{(x_i, x_j)}$  of  $(x_i, x_j)$  as the number of times  $(x_i, x_j)$  has been visited in a given period  $T$ . A street segment  $(x_i, x_j)$  is *covered* if and only if its visiting frequency is greater than or equal to the minimum visiting frequency  $F_{\min}$  required by the target application. It is possible, then, to define  $\mathcal{E}_c$  as the subset of  $\mathcal{E}$  containing all  
305 the covered street sections, which is evaluated in terms of  $D_{\max}$  and  $F_{\min}$ .

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#### Algorithm 1 Algorithm to construct the subset $\mathcal{E}_c$

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**Require:**  $\mathcal{P} = \{P_{b1}, \dots, P_{bn}\}, D_{\min}, F_{\max}$

- 1: **visits\_counters**  $\leftarrow$  **0**
- 2: **for**  $P_{bi} \in \mathcal{P}$  **do** ▷ For the bus path of every bus
- 3:      $m \leftarrow 1$
- 4:     **while**  $m \leq |P_{bi}|$  **do** ▷ For each street section along the path of  $b_i$
- 5:          $delivery\_delay \leftarrow get\_delivery\_delay(P_{bi}, m)$
- 6:         **if**  $delivery\_delay \leq D_{\max}$  **then**
- 7:             **visits\_counters** $[P_{bi}[m]] \leftarrow$  **visits\_counters** $[P_{bi}[m]] + 1$  ▷ Count the number of visits for each section
- 8:          $m \leftarrow m+1$
- 9:  $\mathcal{E}_c \leftarrow \emptyset$
- 10: **for**  $section \in \mathcal{E}$  **do** ▷ Verify the measurement frequency for each section
- 11:      $measurement\_frequency \leftarrow$  **visits\_counters** $[section]/T$
- 12:     **if**  $measurement\_frequency \geq F_{\min}$  **then**
- 13:          $\mathcal{E}_c \leftarrow \mathcal{E}_c \cup section$
- 14: **return**  $\mathcal{E}_c$

---

Algorithm 1 formalizes the construction of  $\mathcal{E}_c$ . The algorithm receives as inputs the set  $\mathcal{P}$ , the limit  $D_{\max}$  and the limit  $F_{\min}$ . The set  $\mathcal{P}$  contains all the paths from the buses. Each path is defined in terms of the street segments of the city. The limits  $D_{\max}$  and  $F_{\min}$  define, respectively, the maximum delivery  
310 delay and the minimum measurement frequency tolerated by the considered application. The array **visits\_counters** is an array indexed by section. In

the while loop starting at Line 4, the visits of each section are accumulated in **visits\_counters**. The function *get\_delivery\_delay* receives as input a path and an index  $m$  in the path. The function returns the delivery delay for the  $m^{th}$  street section of the path. The for loop starting in Line 10 adds to the subset  $\mathcal{E}_c$  the sections that were visited with at least the minimum frequency of measurement  $F_{\min}$ . The algorithm returns the subset  $\mathcal{E}_c$ , containing the street sections that are covered for the considered application. This set is the final output of the algorithm.

Given the reasoning above and the construction of  $\mathcal{E}_c$ , Equation 1 defines the coverage  $C$  of a city for a given application as the sum of the lengths of street segments that are visited within a minimum visiting frequency, normalized by the sum of the length of all the street segments of the city. In Equation 1,  $\mathcal{E}_c$  is the set of covered street segments and  $L$  is the sum of street segments lengths.

$$C = \sum_{(x_i, x_j) \in \mathcal{E}_c} \frac{l_{(x_i, x_j)}}{L}. \quad (1)$$

It is important to notice that the coverage metric proposed is a linear metric. Since we assume a multi-purpose MWSN, we do not infer the sensing range of each sensor. Therefore, we assume the sensing range as the width of each street that a bus passes by. As a consequence, coverage is related to the length of streets covered by each bus.

## 5. Experimental analysis

To show the feasibility of the proposal, we apply the metric to a hypothetical network, derived from real mobility traces of the buses of the city of Rio de Janeiro. Initially, we split the streets of Rio de Janeiro into street segments. After that, we collect traces consisting of GPS coordinates of buses, refreshed every minute. To calculate the coverage using the traces, we must filter the traces and adjust them to the topology of the street segments. To obtain the delivery delay of each measurement, we must access the times when each bus



can make contact with a gateway and, therefore, can deliver data. Finally, we can compute the coverage of the city, for different application requirements.

340 *5.1. Data collection and processing*

To divide the streets of Rio de Janeiro into street segments, we use a map provided by OpenStreetMap [27]. The area of Rio de Janeiro is selected from the map, using a square delimited by the coordinates (-23.07,-43.7) and (-22.78,-43.16). The map is a graph that uses the same model described in Section 4. 345 Therefore, each edge of the graph is a street segment. The sum of all street segment lengths on the map is 13,852 km.

The city administration of Rio de Janeiro provides bus mobility traces through an Application Programming Interface (API) [28]. The API offers a list containing the GPS coordinates of each bus, refreshed every minute. Each element of 350 this list is a tuple containing the bus identification, its coordinates, and a timestamp of the moment when the coordinates are obtained. We have collected 29,155,221 GPS positions of 5,706 buses during the week between November, 5<sup>th</sup>, 00:00, and November, 11<sup>th</sup>, 23:59, in the year of 2,018. Since GPS coordinates are prone to errors, we eliminate inconsistent records. We consider that 355 the records outside the square defined by the map and the records with timestamp out of the gathered period are inconsistent. Also, to reduce the cardinality of the dataset, we eliminate consecutive records of the same bus that differ from less than 10 meters. It is possible to discard these records because the difference between them is within the GPS error, i.e. 10 meters [29]. After these filters, 360 there are 19,979,537 records. Table 4 shows the number of active buses for each day of the week. A bus is considered active if there is at least one entry for this bus in the day. It is possible to note that the largest difference in the number of buses is between Wednesday and Sunday. This difference is of 216 buses, which represents only 4% of the buses. Based on this result, the dataset is not divided 365 into weekdays and weekends.

We also analyze the effect of the time of day when the buses are operating. To do so, we compute the cumulative distance traveled by buses at each moment

Table 4: Number of active buses in the different weekdays.

Day of the week	Number of buses
Monday	5,540
Tuesday	5,546
Wednesday	5,573
Thursday	5,563
Friday	5,547
Saturday	5,435
Sunday	5,357

of the day. Figure 2 shows the result of the total distance traveled as a function of the time of the day. It is possible to observe that between 0h and 4h, the distance traveled is close to zero. Therefore, we choose to eliminate this period of the day of our analysis, trusting that the buses are not capable of collecting data during this interval.

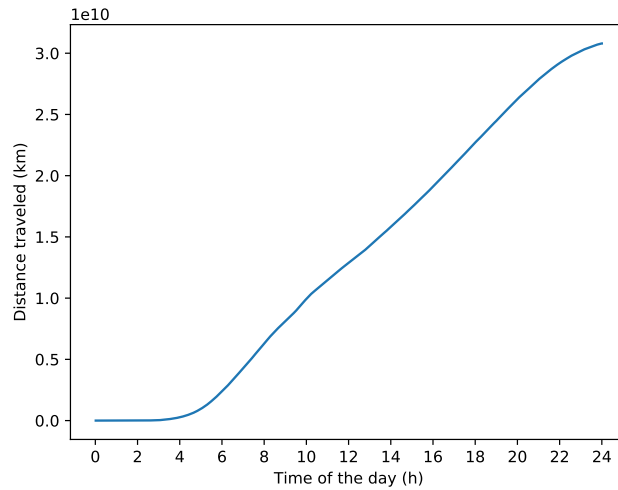
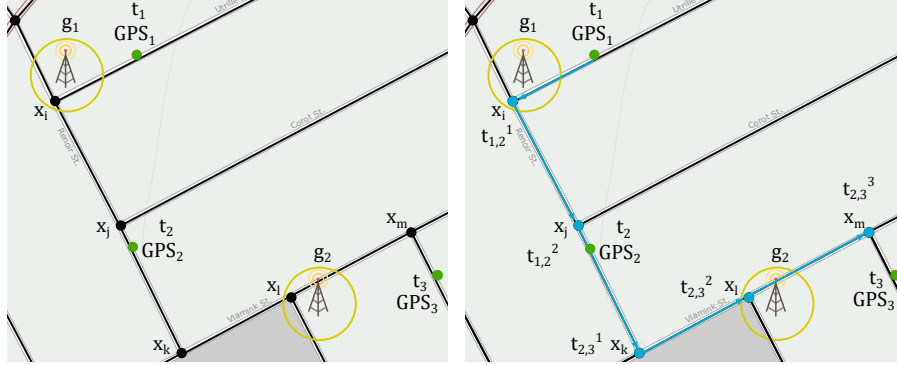


Figure 2: Cumulative distance traveled on each time of the day.

Bus traces have one GPS-coordinate sample per minute per bus. As illustrated in Figure 3(a), the GPS sampling rate does not allow the detection of all the street segments in the path of each bus. It is necessary to obtain the path



(a) Sequence of GPS coordinates from a single bus. (b) Route returned by OSRM, with interpolated timestamps.

Figure 3: Transformation of GPS coordinates into bus paths using OSRM.

of a bus in terms of all the edges in  $\mathcal{G}$  that are part of the path of the bus, i.e., the street segments of the path. Therefore, we use the matching function on Open Source Routing Machine (OSRM) [30]. This function returns the most likely route followed by a vehicle, from a sequence of GPS coordinates. OSRM  
380 returns a route as a sequence of vertices of the map. This way, we obtain the paths of the buses as a list of all the vertices where the buses pass by. With this list, we can derive the street segments visited by each bus.

After obtaining the paths in terms of map vertices, we must also associate to every edge  $(x_i, x_j)$  in a path  $P_b$  the instant when  $b$  passes by this edge. It is  
385 expected that between two consecutive GPS positions, the route generated by OSRM consists of many vertices. Since OSRM identifies the vertices that correspond to a given GPS position in the matching, we associate the timestamp  $t$  of the GPS position to the corresponding vertex returned by OSRM. Then, we use interpolation to associate an instant to the other vertices, employing the  
390 time between vertices as weights. In other words, we assume the bus traveled at a constant speed between those two points. Figure 3(a) illustrates this interpolation, where  $t_{n,n+1}^i$  is the  $i^{th}$  instant estimated by the interpolation between GPS positions  $n$  and  $n + 1$  in the GPS positions sequence.

To determine the time at which a bus can deliver data, it is necessary to  
 395 detect the instants when a bus is in contact with a gateway. Hence, we define  
 that a bus can deliver data when it reaches a vertex that is within communication  
 range of a bus stop. We also define that a node is within communication range of  
 a bus stop when it is in a distance of 10 m or less from this bus stop. Therefore,  
 the bus can deliver data when it is within communication range of at least one  
 400 bus stop. After the processing, it is possible to build the set  $\mathcal{E}_c$  and, finally,  
 evaluate the coverage for different applications.

### 5.2. Coverage analysis

With the data obtained in Section 5.1, we build an abacus of the network  
 coverage. Figure 4 shows the coverage of Rio de Janeiro as a function of  $F_{\min}$ , for  
 405 different maximum delays  $D_{\max}$  of 12 s, 120 s, 300 s, 600 s, 1,800 s, and 72,000 s.  
 As mentioned in Section 2, the case where  $D_{\max}$  is unrestricted (i.e., 72,000 s)  
 and  $F_{\min}$  is minimum (i.e., one) is equivalent to the coverage proposed in [9]. To  
 calculate  $F_{(x_i, x_j)}$ , we count the number of visits received by  $(x_i, x_j)$  and divide  
 it by the period  $T$ . The period used to calculate the measurement frequency  
 410 is of 20 h, since it is the period considered in the traces. If we observe the less  
 restricted case, where  $D_{\max} = 72,000$  s and  $F_{\min} = 1$  measurement per day,  
 we can note that the coverage is 47.4% of the streets of the city. It is also  
 possible to observe that, for  $F_{\min} = 1$  measurement per day, the coverage value  
 for  $D_{\max} = 120$  s more than doubles when compared to  $D_{\max} = 12$  s. In every  
 415 observed case, a change in  $D_{\max}$  or in  $F_{\min}$  implies in a change in the coverage,  
 as a consequence. These results demonstrate the importance of considering the  
 delivery delay when estimating the coverage of such network.

As shown in Table 2, a  $D_{\min}$  of 300 s represents the applications of air quality  
 and noise monitoring, while a  $D_{\min}$  of 1,800 s represents an application of waste  
 420 management. Figure 5 illustrates the coverage for the central region of Rio  
 de Janeiro, for the applications of waste management, air quality monitoring,  
 and noise monitoring. The streets in blue are the coverage of noise monitoring  
 application. Since air quality monitoring application is less restrictive than

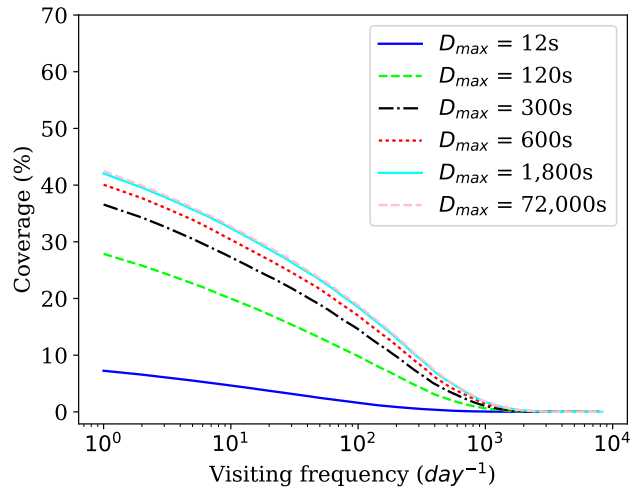


Figure 4: Abacus of the coverage of Rio de Janeiro in function of  $F_{(x_i, x_j)}$ , for different  $D_{max}$  over one week.

noise monitoring, the coverage of this application is equal to the coverage of the  
 425 noise monitoring application plus the street sections in green. The application  
 of waste management is even less restrictive than the application of air quality  
 monitoring. Its coverage is the coverage of air quality monitoring plus the  
 street sections in red. The street sections in gray could not be covered. The  
 area illustrated in Figure 5 has 22.26 km, representing about 1.86% of the total  
 430 area of Rio de Janeiro.

Other values of maximum delay are added to Figure 4 to represent appli-  
 cations that do not have a fixed delay value in the literature. It is possible to  
 observe that the maximum coverage of the network is about 49% of the length  
 of the streets of Rio de Janeiro.

435 Using the delay and frequency thresholds in Table 2, it is possible to de-  
 fine the coverage for different applications for smart cities. Table 5 shows the  
 coverage for some of these applications. This table and Figure 5 show together  
 the differences in coverage obtained with different real-world requirements. We  
 can observe a difference of up to 15.9% in the coverage of the analyzed appli-  
 440 cations. In other words, the coverage more than doubles when we compare the

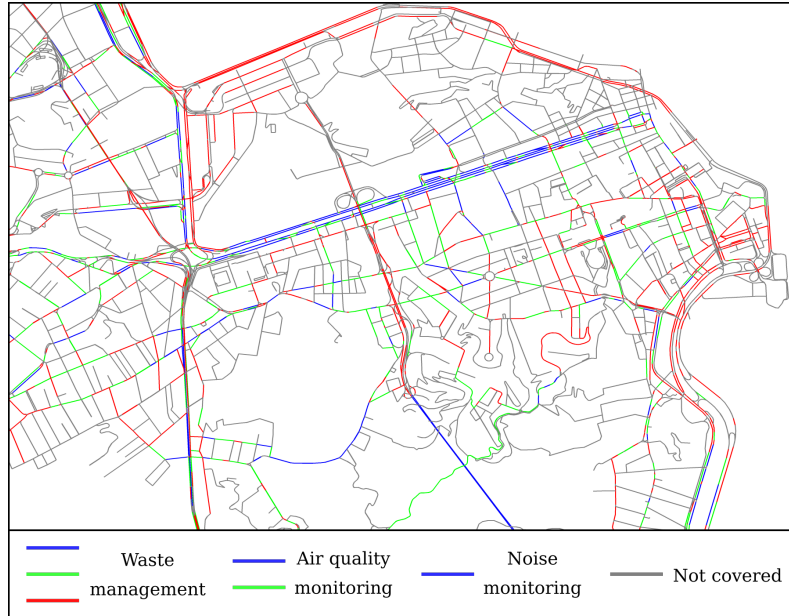


Figure 5: Coverage of the central region of Rio de Janeiro for different smart city applications.

applications of noise monitoring and waste management.

### 5.3. Comparison with another coverage metric

There are many coverage metrics that do not consider the maximum delivery delay  $D_{\max}$  and the minimum measurement frequency  $F_{\min}$  tolerated by each application. The coverage metric proposed by Ali and Dyo is an example of this situation [8]. Their metric counts the number of streets that are visited at least once by any bus. Therefore, in addition to not including  $D_{\max}$  and

Table 5: Coverage obtained by different Smart city applications.

Application	Coverage (%)
Waste management	27.9
Air quality monitoring	19.3
Noise monitoring	12.0

$F_{\min}$ , the length of street segments are also not considered. Even though it appears very similar to our proposal, not considering  $D_{\max}$  and  $F_{\min}$  creates significant difference. To show the importance of considering  $D_{\max}$  and  $F_{\min}$  when estimating also other coverage metrics, we apply the coverage metric by Ali and Dyo to the dataset obtained in Section 5.1. After estimating the coverage by the original model proposed by Ali and Dyo, we adapt their coverage metric to take into consideration  $D_{\max}$  and  $F_{\min}$ .

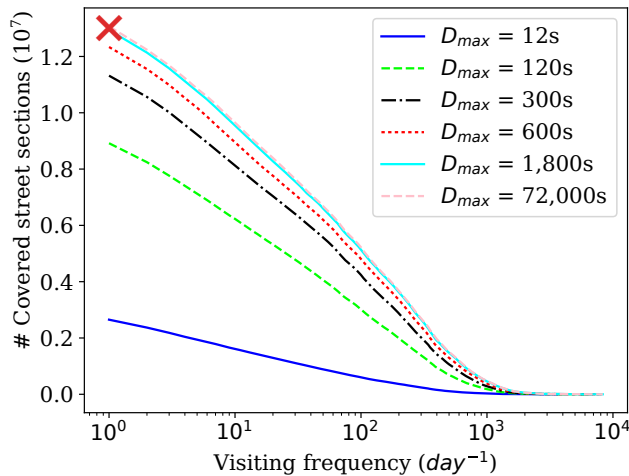


Figure 6: Abacus of the coverage metric proposed by Ali and Dyo for Rio de Janeiro in function of  $F_{(x_i, x_j)}$ , for different  $D_{\max}$  over one week.

Figure 6 shows the coverage as estimated by Ali and Dyo. We also plot the coverage values when different restrictions on  $D_{\max}$  and  $F_{\min}$  are imposed, to show the impact of considering these dimensions. The coverage obtained by Ali and Dyo, signaled by an “ $\times$ ” symbol, is the unrestricted case. In our dataset, this means  $D_{\max} = 72,000$  s and  $F_{\min} = 1$ . It is possible to observe that the coverage obtained by Ali and Dyo overestimates the coverage to any application whose restrictions are tighter than  $D_{\max} = 72,000$  s and  $F_{\min} = 1$ . This result stresses further the importance of considering  $D_{\max}$  and  $F_{\min}$  when estimating coverage, even in the case where the coverage metric ignores the length of streets.

465 *5.4. Comparison with the static case*

The goal of using mobile sensors is to achieve better spatial coverage for certain applications. To quantify the coverage gain, we want to analyze the coverage obtained by leveraging buses mobility with the coverage obtained by a possible static scenario. In the case of bus-based mobility, sensors cover each street segment from its beginning to its end. This is not the case for static sensors. Therefore, it is important to use a method capable of considering the coverage of fractions of street segments. In this static scenario, bus stops are gateways and sensors are placed within their communication range. We consider as covered a fraction of street segment that is inside the communication range of at least one gateway. The total coverage is the sum of the lengths of all covered fractions.

To evaluate the static coverage, we treat each gateway as a circle of radius equal to the communication range. The union of such circles represents the area in the city where communication with at least one gateway is possible. We represent street segments as line segments. The union of these line segments is the total road map of the city. In this metric, the total sensing coverage is the intersection between the area where communication with gateways is possible and the road map of the city. The idea behind it is that it is possible to place static sensors anywhere in the communication range of gateways. Figure 7 illustrates the coverage by static sensors placed in the communication range of gateways. The evaluations show a total static coverage of 1,7% of the total roads on the map. The static coverage obtained is equivalent to about 242 km of streets.

Figure 8 shows the gain of coverage obtained by the bus-based mobility of sensors over the course of a week. It is possible to notice that the coverage gain for an application of waste management ( $D_{\max}=1,800$  s ,  $F_{\min}=24$  per day) is more than 16.4 times, while for the applications of air quality ( $D_{\max}=300$  s,  $F_{\min}=48$  per day) and noise monitoring ( $D_{\max}=300$  s,  $F_{\min}=144$  per day) are 11.6 and 7.6, respectively. Table 6 shows, for each  $D_{\max}$  analyzed, the maximum  $F_{\min}$  that could benefit from the mobility. In other words, it shows the



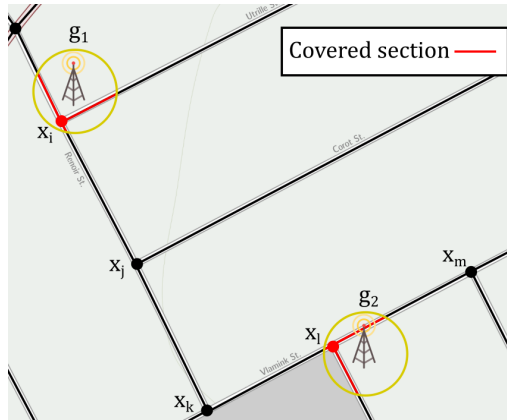


Figure 7: Example of covered streets by static sensors placed within communication range the gateways.

tightest application requirements that could be satisfied by the mobile network and still improve coverage. These results show that the coverage of smart city applications can largely benefit from the mobility provided by buses.

## 6. Conclusion

500 Mobile Wireless Sensor Networks (MWSNs) are an option to decrease the sensing cost of a large area. On the one hand, the mobility increases the region covered by each sensor and lowers the networking costs, through delay-tolerant data delivery. On the other hand, regions are not covered the whole time and sensed data is not delivered instantly. In the scenario where buses are used to

505 enable sensors with mobility, there are different visiting frequency and delivery delay for different streets. Since smart city applications have different data needs, each application can benefit from data gathered from different streets. Consequently, the coverage of the network is not the same for different applications.

510 This work proposes a coverage metric that takes into account the minimum visiting frequency and the maximum delivery delay tolerated by an application. The metric is used with real traces from buses of the city of Rio de Janeiro, in

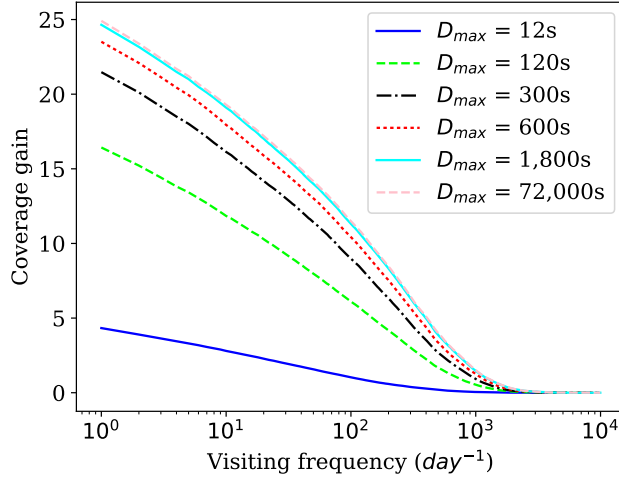


Figure 8: Coverage gain by buses of Rio de Janeiro in comparison to a static network, in function of  $F(x_i, x_j)$ , for different  $D_{max}$  over one week.

a scenario where bus stops are gateways. We present our results in the form of an abacus. Therefore, it is possible to obtain the coverage of the network, given  
 515 a certain application that requires a minimum visiting frequency and maximum delivery delay. We also obtain the coverage of applications that have known minimum visiting frequencies and maximum delivery delays in the literature. We found that a waste management application can cover 27.9% of the city of Rio de Janeiro using the buses of the city. We also show that, for this  
 520 application, buses increase the coverage of the network up to 16.4 times, when compared to the scenario where sensors are static.

As future works, we plan to investigate the effect of using other communication technologies and more realistic propagation models. We believe that changes in the communication links can change the trade-off between mobile  
 525 and static scenarios. We also plan to evaluate the effects of recruiting other vehicles and pedestrians for coverage. Another possible extension is to measure the impact of different gateway distribution on system performance.

Table 6: Applications requirements limits to benefit from the mobile scenario.

$D_{min}$ (s)	$F_{min}$ ( $day^{-1}$ )
12	105
120	715
300	960
600	1110
1,800	1203
72,000	1219

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