Towards Enabling Mobile Social Crowd-Sensing for Unstructured Transport Information Management: Performance Evaluation of Large-Scale End-to-End Publish/Subscribe Interaction

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Abstract

Developing countries are characterised of chaotic large-scale traffic, especially in major cities. Robust mobile systems for information concerning transport services are of critical importance. Additionally, although most of the people have mobile phones, even smartphones, a large part of the population rely on SMS data access only. The situation of Senegal reflects the above. In this paper, we take a first step towards enabling an *application platform for citywide and countrywide transport information management* relying on 'mobile social crowd-sensing'. To inform the stakeholders of expected loads and costs, we model a large-scale mobile publish/subscribe system as a queueing network. We introduce additional timing constraints such as (i) mobile user's intermittent connectivity period; and (ii) data validity lifetime period (e.g. that of sensor data). Using our *MobileJINQS* simulator, we parameterize our model with realistic input loads derived from the *D4D* dataset and varied lifetime periods in order to analyze the effect on response time. This work provides system designers a coarse grain design time information when setting realistic loads and time constraints.

Keywords: Publish/Subscribe, Mobile Social Crowd-Sensing, Large Scale, Queueing Networks, Transportation Systems

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1. Introduction

A reliable and efficient transportation system is a key growth indicator for a country. The transportation system of Senegal, although developing, still consists of many unplanned and informal settlements with unreliable services and infrastructure [11, 2]. This applies to both countrywide transportation system (e.g., road network and buses, railway) and urban transportation system (e.g., taxis and buses in Dakar). Particular conditions include high traffic of people and merchandise between Dakar and the rest of the country, and movement of population during religious festivals. In this context, the native population and the visitors greatly benefit from information concerning transport services and schedules, as well as timely reports about transport conditions and unexpected events. However, use of the Internet by transport providers and travellers in Senegal remains limited. Indicatively, recent reports show that 31% of SMEs in Senegal have Internet access, with only 7% having a website [1]. Additionally, despite the fact that most of the people have mobile phones, only 26% of them have mobile Internet access [7] in Senegal. The above percentage is almost equal to the total Internet access, as use of fixed Internet remains very low. Hence, for a large part of the population, the only alternative for data access is SMS.

Considering the above limitations in Senegal, we propose the development of an *application platform for citywide and countrywide transport information management* relying on 'mobile social crowd-sensing'. Leveraging the massive adoption of mobile phones by the population, mobile social crowd-sensing enables a user to 'sense' and report on the environment with respect to personal, social or public context. This complements the objective and the authoritative information coming from structured information sources and compensates for the lack of such information. Such a rich data, after careful processing, can be used not only to directly inform the population, but also to develop advanced services for local stakeholders and to drive studies and policies for state authorities. Our application platform would enable development of mobile applications and related support systems for transport information in Senegal, hence contributing to the improvement of travel experiences in the country.

In our approach, we study and experiment with appropriate interaction styles (based on message-passing, events, data sharing) on top of 3G/2G/SMS data connections (or even future 4G [10]), further depending on the specific application and data. For this, we rely on our ongoing work on *Extensible Service Bus, (XSB)* [5], a framework for handling interconnection between interaction protocols applying the above-mentioned interaction styles. We are particularly interested in interaction adaptation depending on the network conditions (e.g., switching to SMS-based protocol when the 3G/2G network is unavailable). Furthermore, we deal with large-scale sensing interactions, as we are targeting large-scale deployments. For this, we build upon our recent work on *MobIoT* [6], a service-oriented middleware enabling efficient sensing over ultra-large population of mobile sensors.

In this paper, we take a first step towards enabling an application platform for transport information management based on mobile social crowd-sensing keeping in mind the particular context and constraints of Senegal. This consists of evaluating the publish/subscribe interaction style in a large-scale setting where resources of mobile users are limited, which translates into limited and intermittent connectivity in the system. We have opted for the publish/subscribe paradigm, as it is deemed appropriate for spatio-temporal interaction between mobile entities.

More specifically, we introduce a queueing network model for the end-to-end interaction within a large-scale mobile publish/subscribe system. We leverage the dataset provided by Orange Labs to parametrize this model. We refer to this dataset as the ***D4D dataset*** [9]. We then develop a simulator named *MobileJINQS*[1] that implements our model and uses the dataset traces as realistic input load to the system model over the time span of a whole year. Prior to this, we extensively analyze the *D4D* dataset in order to identify the data

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[1] `http://xsb.inria.fr/d4d#mobilejinqs`

that we are interested in and infer primary results. Based on the results of our simulation-based experiments, we thoroughly evaluate the behavior of the publish/subscribe system and identify ways of tuning the system parameters in order to satisfy certain design requirements.

The rest of the paper is structured as follows: in Section 2, we summarize our analysis of the *D4D* dataset. In Section 3, we introduce our model, its parametrization based on the dataset, and our simulator. Then, we present, in Section 4, our simulation experiments and their outcomes. We finally conclude this paper in Section 5.

2. D4D Dataset Analysis

In this section, we provide a brief description of how we analyze the real data provided to us by Orange Labs in order to parametrize and feed our simulation model described in the next section. The dataset or the *D4D* dataset contains Call Detail Records (**CDR**) of the users that are subscribed to the Sonatel services in Senegal. This data is collected over a period of 1 year (Year 2013). The *D4D* dataset consists of 3 sub-datasets: *Dataset1* consists of number of calls and duration of calls made during an hour, *Dataset2* consists of fine grain spatial user mobility trace, while *dataset3* consists of coarse grain spatial user mobility trace. It should be noted that as the dataset collected is a *CDR*, the logs in *Dataset2* and *Dataset3* are made only when the user initiates a call or sends an SMS.

From the *D4D* dataset we chose **Dataset2** for the realization of the model on a large scale. We choose *Dataset2* due to the fine spatial granularity of the dataset. Further, properties of *Dataset2* include a) temporal granularity of 10mins b) observations spanning over the year 2013 c) track of almost 300,000 unique users. *Dataset2* reflects the mobility pattern of a single user and also the number of users associated to a given antenna in a given time interval. This lead us to first extract number of people associated to a given antenna in a given time interval.

Let A be the set of Antennas, T be the set of unique time intervals over which the data is collected and U be the set of users tracked in the *Dataset2*. Let $\mathbf{P}$ be a $|T| \times |A|$ matrix.

Definition 1. *Let N_i^t be the number of people associated to antenna $i \in A$ at a given time $t \in T$ then*

$$\boldsymbol{P}_i^t = N_i^t$$

Note that, N_i^t also denotes number of connections made to the antenna $i \in A$ at a given time $t \in T$. From $\mathbf{P}$ we extract how many users are present at a given time interval on a country scale.

Definition 2. *Let N_c be the matrix of size $|T| \times 1$ such that element N_c^t is the number of users in a country at time interval $t \in T$. Then*

$$N_c^t = \sum_{\forall i \in A} \boldsymbol{P}_i^t$$

Let $MaxN$ be a matrix of size $|A| \times 365$ where $MaxN_i^d$ represents the max number of people in an antenna i on a given day d.

Definition 3. *Let Day be the set of unique days of the year. Let $TimeSlot$ be the set of all unique time intervals on a given d, then for $d \in Day$*

$$MaxN_i^d = \max_{t \in TimeSlot} (\boldsymbol{P}_i^t)$$

Note that $T \supset TimeSlot$.

We provide visualization of $\mathbf{P}$ from Jan 07, 2013 00:00:00 until Jan 20, 2013 23:50:00 (Cf. Fig. 1). An animated version of the same is available here[2]. From the visualization we observe that most of people are located near Dakar region and in the major cities in the west and north west of Senegal (north of Gambia). The population graphs also show less utilization of infrastructure during the night hours. It should be noted that the antenna IDs are marked from west to east (Cf. Fig. 2). The Fig. 3 shows N_c^t.

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[2] `http://xsb.inria.fr/d4d#visualization`

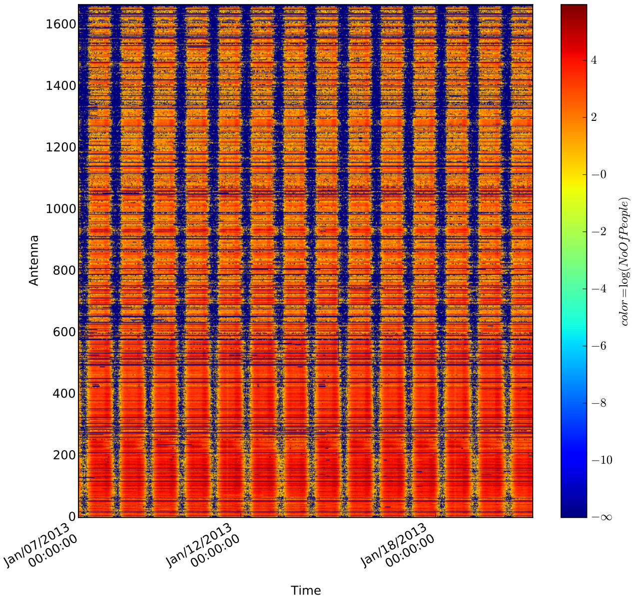

Figure 1: Visualization of $\mathbf{P}$.

From the Def. 3 we extract $\max_{\forall t \in T}(N_c^t)$, the max number of people in the whole system (Country) at any given time interval t such that $t \in T$. From the *Dataset2* $\max_{\forall t \in T}(N_c^t) = 112,937$ observed on Thu, 08 Aug 2013 from 23:00:00 to 23:10:00 GMT, i.e., on the End of Ramadan, a public holiday in Senegal. Note that this number is different from the number of unique users tracked because some users might appear only at some distinct times while being inactive for other times. The Fig. 4 provides the visualization of $MaxN$. Fig. 4 shows that over a day, antenna IDs in $A' = [1, 580)$ have lot of users as compared to users in $A - A'$. It should also be noted that there are some antennas where the users were not tracked over the entire period of the year 2013. This is also represented in the Fig. 4.

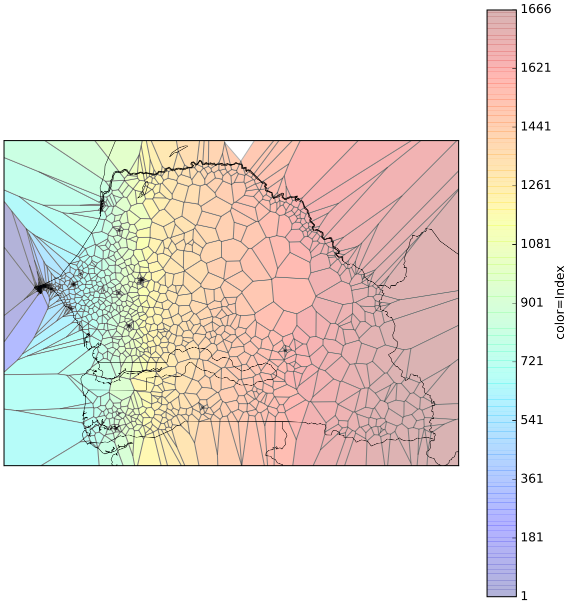

Figure 2: Representation of Antenna IDs.

3. Publish/Subscribe Performance Model

Our main objective in this work is to enable large-scale sensing interactions that are part of a mobile social crowd-sensing application. Particularly, we target an application platform for citywide or countrywide transport information management based on unstructured information posted by mobile users. In terms of communication infrastructure support, we rely on the publish/subscribe interaction paradigm that provides loosely coupled form of required interaction, especially in large-scale environments [3]. Additionally, such an application platform must guarantee that the sensing data is processed and delivered to the corresponding mobile users **on-time**, despite the intermittent connectivity of the latter for resource-saving purposes. To ensure the freshness of the delivered data, events are characterized by a validity period, after the expiration of which

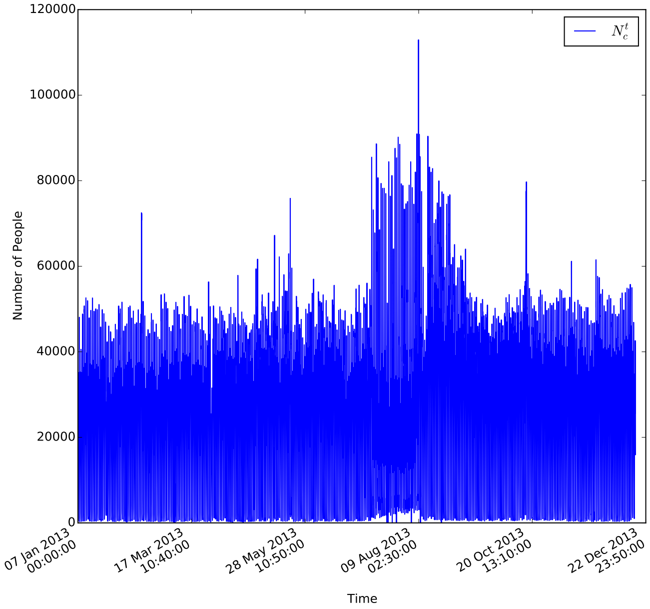

Figure 3: Visualization of N_c.

they are discarded by the system. In the following sections, after a brief presentation of the publish/subscribe interaction paradigm, we introduce our model that encompasses the above concerns. We then detail the parameterization and simulation of the model based on the D4D dataset.

3.1. Publish/Subscribe interaction paradigm

In the publish/subscribe interaction paradigm, multiple peers either take the role of publisher or a subscriber and interact via an intermediate broker. Publishers produce events characterized by a specific topic to the broker. While subscribers subscribe their interest for specific topics with the broker, who maintains an up-to-date list of subscriptions. The broker matches received events with subscriptions and delivers a copy of each event to each interested subscriber. This style of interaction is decoupled. In terms of space coupling, interacting

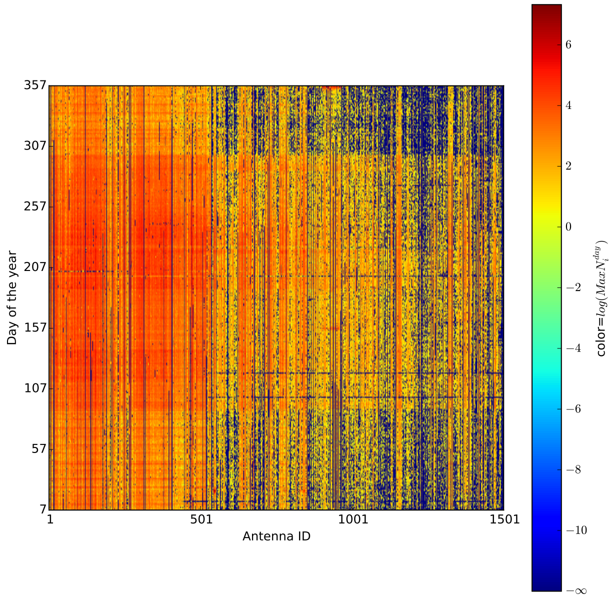

Figure 4: Visualization of $MaxN$.

peers do not need to know each other. Events are diffused to subscribers only based on topics (one-to-many interaction). In terms of time coupling, peers do not need to be present at the same time during interaction. Subscribers may be disconnected at the time when the events are published to the broker, who then keeps the events in a dedicated buffer for each subscriber. Thus, subscribers receive the pending events when reconnected.

3.2. Large-scale mobile publish/subscribe system

A large-scale publish/subscribe system relies on a network of *brokers*. It may be the case that all brokers are accessible to publishers and subscribers, or that there is a distinction between *edge brokers* (brokers at the periphery of the network) and *brokers situated in the network backbone* (core brokers). In both cases, each broker propagates the subscriptions it receives to its neighbors, thereby populating the routing table of each broker.

In a large-scale *mobile* publish/subscribe system, publishers and subscribers are mobile entities. Interactions then rely on volatile network access to the nearest edge broker. Publishers connect to the system to publish events. They may set a *lifetime* limit to these events, depending on the nature of the specific application and data. Subscribers connect occasionally to the system to receive new events, and disconnect to save energy. While moving, a subscriber may hand off between brokers. This results in each broker updating their subscriptions and routing table as well as transferring between them the events stored for the subscriber but not yet delivered.

3.3. End-to-end interaction model of a large-scale mobile publish/subscribe system

In our study, we focus on end-to-end interaction between publishers and subscribers going through two access points of the system, an *input access point* and an *output access point*. The *input access point* is provided by an edge broker. Geographically close mobile publishers generate input flow to the whole system through this access point. The *output access point* is also provided by an edge broker. Geographically close mobile subscribers receive output flow from the whole system through this access point.

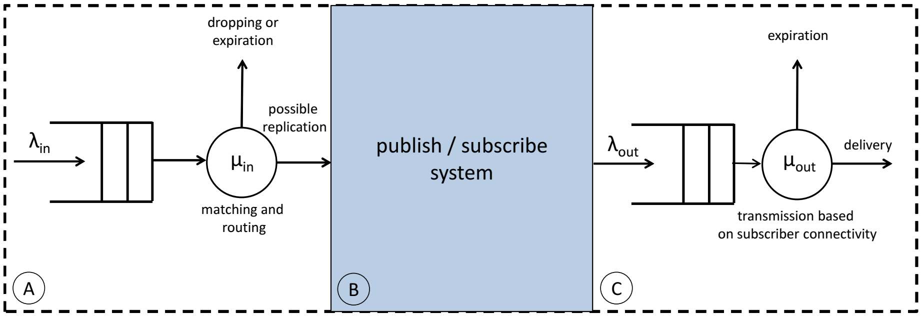

Figure 5: End-to-end interaction between publishers and subscribers through two system access points

The *input access point* is modeled as a queueing system where the service delay μ_{in} represents matching incoming events (input flow λ_{in}) to subscriptions and routing them to corresponding subscribers and/or brokers (part A of Fig. 5). This may involve replication of some events. This may also involve dropping of some events, either due to no corresponding subscription or due to expiration.

The *output access point* is modeled as a queueing system where the service delay μ_{out} represents the transmission of buffered events to the intermittently connecting subscribers previously determined by routing (output flow λ_{out}), as depicted in part C of Fig. 5. Here again, some events may expire before being delivered to their destination.

We focus only on the input and output processes. We do not consider, for the moment, the rest of the publish/subscribe system (i.e., multiple input and output access points, routing of events among multiple brokers). Additionally, we link directly the output of the first queueing system to the input of the second one, considering the path through the publish/subscribe system as a simple wire. This is equivalent to having a single centralized broker for the whole publish/subscribe system. Again, in this paper, we intend to restrict our model to only certain features.

3.4. Use of the dataset to parametrize the model

For parametrizing our model, we rely on our *D4D* dataset analysis presented in Section 2. More particularly, we are interested in $\mathbf{P}_i^t$, the number of users associated to a given antenna $i \in A$ (or number of connections to this antenna) in a given time interval $t \in T$ over the whole recording time period T of Year 2013. We select from the set A, A' such that $A \supset A'$ where A' consists of antennas i with large $MaxN_i^d$. Note that, these antenna IDs are between 1 through 579. These antennas are located mainly in the Dakar region and in the major cities in the west and north west of Senegal. While loads of the selected antennas are quite different in terms of mean value and variance, almost all of them present their peak around the End of Ramadan, as identified in Section 2.

We map the two access points of our publish/subscribe system model to two antennas identified in the dataset. We use, in particular, the trace providing the number of connections to an antenna every 10 minutes for a period of 50 weeks. Each such connection corresponds to the initiation of a call or the emission of an SMS from the specific antenna. We make the assumption that this trace can equally represent the reception of a call or an SMS through the antenna. For the input access point, we map the number of connections per 10 min interval at the selected antenna to an equal number of events published over the same time interval.

Definition 4. *Let* λ_{in} *be the input process at the input access point associated to the antenna* $i \in A$*, and* $\boldsymbol{P}_i^t$ *be the number of connections to the antenna* i *in each interval* $t \in T$*, as defined in Def. 1. Then* λ_{in} *is a non-homogeneous Poisson process with rate parameter* $\lambda(t)$ *piecewise constant in each interval* $t \in T$*:*

$$\lambda(t) = \frac{\boldsymbol{P}_i^t}{|t|}$$

For the output access point, we map the number of connections per 10 min interval at the selected antenna to an equal number of events delivered to subscribers over the same time interval, *provided that there are enough events in the queue*. This relates to the number of subscribers that are connected to the access point during the specific interval, i.e., that are available to receive new events waiting for them if any. To provide this effect, we model the service process at the output access point accordingly.

Definition 5. *Let* μ_{out} *be the service process at the output access point associated to the antenna* $j \in A$*, and* $\boldsymbol{P}_j^t$ *the number of connections to the antenna* j *in each interval* $t \in T$*, as defined in Def. 1. Then* μ_{out} *is a non-homogeneous Poisson process with rate parameter* $\mu(t)$ *piecewise constant in each interval* $t \in T$*:*

$$\mu(t) = \frac{\boldsymbol{P}_j^t}{|t|}$$

This is equivalent to having service time of events that follow an exponential distribution with mean equal to $\frac{1}{\mu(t)}$ for the interval t.

The output λ_{out} of the queueing system modeling the input access point is a process similar to the input λ_{in}, provided that the queueing system does not saturate. Then, the λ_{out} is fed to the input of the queueing system modeling the output access point. We also need to take into account the possible replication and dropping of events; this results in $\lambda_{out} \neq \lambda_{in}$. Without loss of generality, we consider that in our setup there is no replication of events or dropping due to the absence of corresponding subscription; however, events may still be dropped due to expiration.

Since interaction in the publish/subscribe system is time-decoupled, any two antennas can be selected. Nevertheless, having λ_{out} (or λ_{in}) $> \mu_{out}$, in terms of overall mean values or over specific time intervals, will result in high numbers of expired events. This is when the event input flow to the system is higher than the event delivery flow constrained by the limited availability of the subscribers.

3.5. Simulation of the model

We have developed a simulator that implements our model and uses the dataset to parametrize the model. The results of our experiments enable thorough analysis of the behavior of the system and can assist a system designer in the configuration of the system parameters in order to satisfy a set of design requirements.

Our simulator, *MobileJINQS*, is an open-source library for building simulations encompassing constraints of mobile systems. *MobileJINQS* is an extension of *JINQS*, a Java simulation library for multiclass queueing networks [4]. *JINQS* provides a suite of primitives that allow developers to rapidly build simulations for a wide range of stochastic queueing network models. However, JINQS only supports the base characteristics of the queueing networks.

MobileJINQS retains the generic model specification power of *JINQS*, while providing additional features of interest to mobile or other systems such as: (i) lifetime limitation for each customer entering a queue, (ii) intermittently available (on-off) queue server or server with variable service rate over time to represent mobile users' behavior, and (iii) input flow with variable customer arrival rate over time to represent real input dataflow traces. In particular, a system designer is able to set lifetimes, on-off intervals, as well as variable service rates and arrival rates following well-known probability distributions.

By relying on the *D4D* dataset traces as detailed in the Section 2, we setup and execute a set of experiments with *MobileJINQS*. Our experiments and their results are presented in the following section.

4. Simulation Results

In this section, we provide results of simulations using *MobileJINQS* of our publish/subscribe system with varied incoming loads, service delays and lifetime periods. We use the dataset to derive realistic traces for incoming loads and service delays. System designers are able to tune the system by selecting appropriate lifetime periods. We demonstrate that varying incoming loads and service delays has a significant effect on response time. In the case of varying lifetime periods, the tradeoff involved between the rate of successful event transactions and response time is also evaluated.

4.1. Selecting representative input load

As identified in Section 3.4, we select from the set A, set A' such that $A \supset A'$ and A' has antennas with large $MaxN_i^d$. Then, traces are derived through number of connections to an antenna at each 10 min interval for a period of 50 weeks. To perform our simulations with varied traces, we classify the load of each selected trace into three main categories: (i) *low load antenna*; (ii) *medium load antenna* and (iii) *high load antenna*. Fig. 6 depicts four antennas used for the experiments of this section. **Antenna 9** has a low load trace with overall average rate 0.04 number of connections for a period of 50 weeks. **Antennas 24 and 14** have medium load traces with overall average rates 0.075 and 0.082, respectively. Finally, *antenna 161* has a high load trace with overall average rate 0.129.

4.2. Response time of our simulation model

Fig. 5 represents the model used for the simulation. To get end-to-end response time between input and output access points, we tune the system with

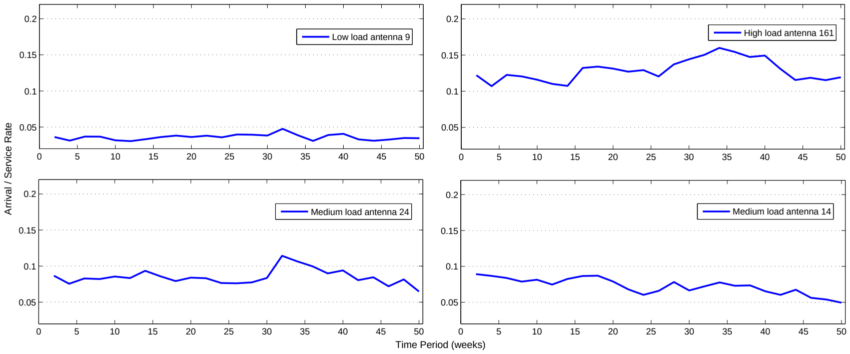

Figure 6: Low, Medium and Hign load of antennas used for our experiments

parameters: (i) input flow λ_{in}; (ii) in service delay μ_{in}; and (iii) out service delay μ_{out}. In this experiment, to avoid high response time or event expiration rate we choose $\lambda_{in} < \mu_{out}$.

At the input access point, we map the load of Antenna 9 to the input flow λ_{in}. Particularly, we correspond the number of connections of an antenna to the number of events for publishing at each 10 min interval over the whole period. The service delay μ_{in}, that is responsible for the transmission of events into the output access point, is set to 1 event per second. This means that we consider rapid event transmissions to avoid event expirations at the input access point.

At the output access point, the output flow λ_{out} is equal to the input flow λ_{in}, provided that our queueing system does not saturate. For the service delay μ_{out}, we map the load of antenna 161. Particularly, we correspond the number of connections of an antenna to the number of connected subscribers at each 10 min interval over the whole period. At a 10 min interval each connected subscriber is receiving one single event (i.e., subscribers' connectivity rate $= 1$). Finally, in this experiment we consider infinite lifetime period for each event transaction.

Transaction response times are shown in Fig. 7 over a period of 50 weeks where users' connectivity rate equals to 1. We depict samples of response times every 2-weeks period. The minimum response time for all end-to-end transac-

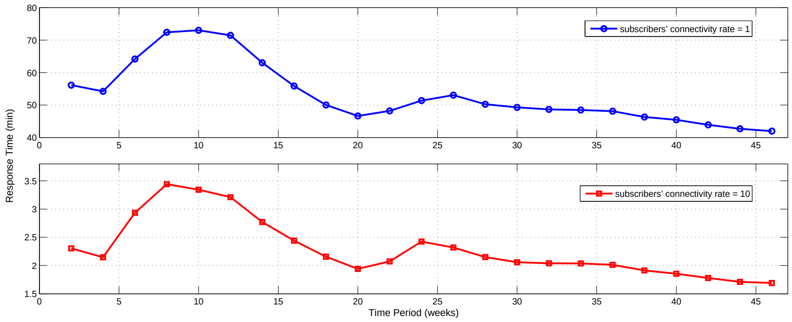

Figure 7: End-to-end transaction Response Times from low load Antenna 9 to high load Antenna 161

tions is 40 mins due to the fact that subscribers may be disconnected for a long period. Between 5th and 15th week, we get a higher response times (73 mins). This implies that, rate of incoming events is much more higher than the rate of subscribers' connectivity.

Consequently, getting lower response times depends on subscribers' behavior. Fig. 7 shows response times if we change the subscribers' behavior by multiplying connectivity rate with 10. This means that and they connect 10 times more for receiving events. By this way, the maximum and minimum response times are 3.5 mins and 1.8 mins respectively.

4.3. Response time vs Success Rate with varying lifetime periods

Based on the previous experiment, the only way to off tune the system in order to satisfy certain design requirements (lower response time), is to change the subscribers' behavior. In fact, a system designer cannot change this. Therefore, it is essential to keep subscribers' behavior invariant and find other ways to satisfy our design requirements. Data sent from input access point is valid for a limited lifetime period (in case of transportation, data of a traveler reporting some incident is valid for a lifetime period, for instance).

In this simulation experiment, we keep the same settings as previously and we introduce the lifetime period at each input event. Lifetime period is following an

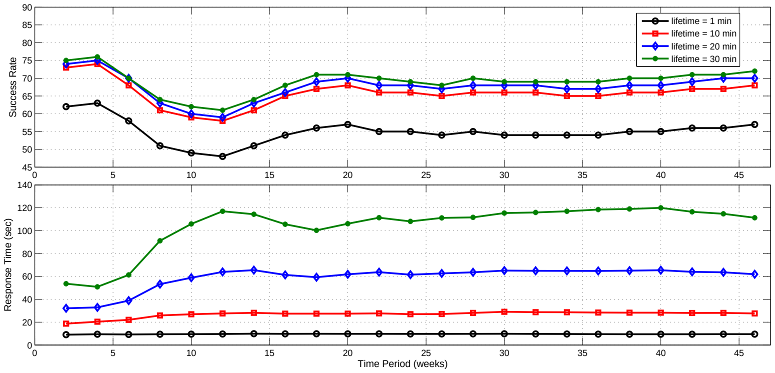

Figure 8: End-to-end transaction Response Times and Success Rates from low load Antenna 9 to high load Antenna 161 with varying lifetime periods

exponential distribution with mean values of 1, 10, 20 and 30 mins. End-to-end response times and success rates are shown in Fig. 8. As expected, with higher levels of lifetime periods, we notice high success rates, but also much higher response time over the 50 weeks period. More specifically, by increasing the lifetime period, response time gets higher quickly, but the success rate increases very little. When lifetime period equals to 1 min, we get the minimum response time equals to 9.5 seconds with message success rate 62 %.

Then, we simmulate different pairs of antenna loads at the input/output access points. We use the antennas shown in Fig. 6 and perform experiments for 3 different types of end-to-end transactions: input access point with medium load to output access point with (i) low load; (ii) medium load; and (iii) high load antennas.

Fig. 9 shows the mean value of response time and success rate for the 50 weeks period. For the first transaction, success rate is very low (0.04 %) even by using 30 min of lifetime period. In the other hand, response time is much higher comparing to the other pairs. For the second transaction, success rates are between 10 - 20 % with response times between 2 - 7.5 mins. Finally, for the third transaction, we get 35 - 50 % success rate with reasonable response times of 0.3 - 2.2 mins.

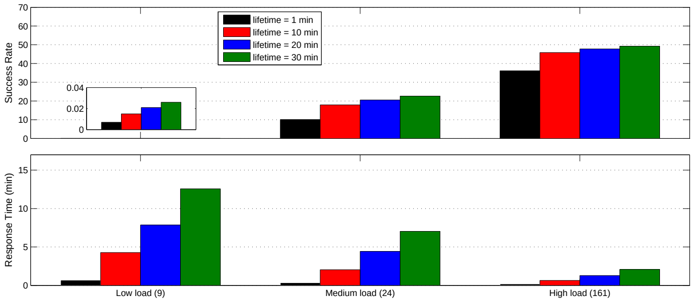

Figure 9: Mean end-to-end transaction Response Times and Success Rates between Medium load Antenna and Low, Medium, High load Antennas with varying lifetime periods

5. Conclusions

In this work, to enable mobile social crowd-sensing for unstructured transport information management in Senegal, we study the behavior of the underlying communication infrastructure under load. We rely on the publish/subscribe interaction style to provide loosely coupled form of the interactions with additional constraints, in large scale environments. Properties such as intermittent connectivity of mobile users and freshness of delivered events, are modeled using a queueing network for an end-to-end interaction. *MobileJINQS*, implements our model and leverages incoming loads and service delays derived from the *D4D* dataset. We demonstrate that varying incoming loads and service delays have a significant effect on response time. Furthermore, by introducing varied lifetime periods in the published events, we evaluate the trade-off between the rate of successful event transactions and response time. Our future work includes comparison of publish/subscribe interaction paradigm with other interaction paradigm (message-passing, data sharing), in relation with the network access capacity and the application requirements. Also, we intend to study the response time and success rate for the various combinations of antennas in more fine-grained scales (e.g., check what their evolution is over one day).

6. Acknowledgement

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7. References

[1] Financial Afrik. La Chambre de Commerce de Dakar et Orange Business Services pour booster lentreprenariat au Sénégal. `http://www.financialafrik.com/2014/04/17/la-chambre-de-commerce-de-dakar-et-orange-business-services-pour-booster-lentreprenaria` April 2014.

[2] ASIRT. Road Travel Report: Senegal. `http://www.asirt.org/portals/0/Reports/Senegal.pdf`, 2009.

[3] Patrick Th Eugster, Pascal A Felber, Rachid Guerraoui, and Anne-Marie Kermarrec. The many faces of publish/subscribe. *ACM Computing Surveys (CSUR)*, 35(2):114–131, 2003.

[4] Tony Field. JINQS: An extensible library for simulating multiclass queueing networks, v1. 0 user guide, 2006.

[5] Nikolaos Georgantas, Georgios Bouloukakis, Sandrine Beauche, and Valerie Issarny. Service-oriented Distributed Applications in the Future Internet: The Case for Interaction Paradigm Interoperability. In *European Conf. on Service-Oriented and Cloud Computing*, 2013.

[6] Sara Hachem, Animesh Pathak, and Valerie Issarny. Service-oriented middleware for large-scale mobile participatory sensing. *Pervasive and Mobile Computing*, 10:66–82, 2014.

[7] ITmag. Exclusivité : Tigo nouveau leader de lInternet mobile au Sénégal. `http://www.itmag.sn/news/exclusivite-tigo-nouveau-leader-de-linternet-mobile-au-senegal`, June 2014.

[8] Edward D Lazowska, John Zahorjan, G Scott Graham, and Kenneth C Sevcik. *Quantitative system performance: computer system analysis using queueing network models*. Prentice-Hall, Inc., 1984.

[9] Orange. Data for development. `http://www.d4d.orange.com/en/presentation/data`.

[10] TeleGeography. Senegals mobile operators to all deploy 4G pilot trials before year-end, Reuters. `http://www.telegeography.com/products/commsupdate/articles/2013/12/11/senegals-mobile-operators-to-all-deploy-4g-pilot-trials-before-year-end-reuters`, December 2013.

[11] Wikipedia. Transport au Sénégal. `http://fr.wikipedia.org/wiki/Transport_au_Senegal`.