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BLUETOOTH-BASED FLOATING CAR OBSERVER: MODEL EVALUATION USING SIMULATION AND FIELD MEASUREMENTS

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1 INTRODUCTION

The knowledge of the current traffic state is a substantial requirement of traffic control and traffic management. Therefore, reliable and high resolution traffic data is needed. The increasing spread of information and communication technologies allows innovative traffic monitoring systems and acquisition methods for generating spatiotemporal traffic data. Radio-based technologies such as Bluetooth or WiFi provide individual information of traffic participants. This information is independent of the observed traffic mode and therefore allows an area-wide observation of journeys executed throughout road networks. The German Aerospace Center (DLR) developed DYNAMIC, a traffic monitoring approach, which combines the advantages of a Floating Car Observer (FCO) monitoring system with the use of a Bluetooth-based sensing module. That means, a Bluetooth-based Floating Car Observer acts as mobile sensor within the traffic flow and observes all traffic participants (vehicles, cyclists, pedestrians) equipped with Bluetooth-enabled devices while passing these traffic objects on the road. By referring to the unique electronic device address (MAC) as an identifier, a major benefit results from recognition possibilities. Thus, particularly desired traffic data such as origin-destination information can be derived.

The central issue - besides data protection concerns – is the prediction of the likelihood of a (re-)detection of such a Bluetooth-enabled moving traffic object. Since Bluetooth has a wide detection range of up to 100 meters and a complex connection establishment process (so called Inquiry Process, cf. chapter 3), one cannot say how much time is needed to detect a certain device and which position that device has exactly had when it was monitored within detection range. That means, one has to know how likely it is that a detectable moving traffic object within the detection range will actually be monitored. Given the possibly high speed of the vehicles and the relatively small detection range this poses a major problem to the DYNAMIC detection approach.

The paper firstly describes the state of the art concerning traffic data acquisition by introducing the current data collection methods as well as the original Floating Car Observer (FCO) idea, which initially was intended for using a video-based sensor system to monitor the surrounding traffic objects. Afterwards, the Bluetooth-based FCO is explained in detail. In chapter 4 a theoretical detection probability model is given, which is evaluated by using microscopic simulation and field measurements as described in chapter 5.

2 STATE OF THE ART

2.1 CURRENT METHODS OF COLLECTING TRAFFIC DATA

Traffic data acquisition for the usage by traffic management systems currently relies on local detection methods, such as inductive loops, stationary camera systems, laser scanners or ultrasonic sensors, which are characterised by spatial limitations in their informative value (see ① in Fig. 1). Therefore, these local measurements do not allow the reproduction of current traffic states in a link-based or area-wide manner. A second method is the instantaneous data collection, which refers to the present traffic state on an entire link (see ② in Fig. 1). Actually, this method cannot be put easily into practice, since automated measuring in its usual stationary mode (e.g. using a video camera system) is also spatial limited due to required mounting heights. Alternatives may be observation flights or satellite remote sensing (see ④ in Fig. 1) which are very cost-intensive. Thus, instantaneous observation has only limited practical impact. (cf. Listl (2003), Wolf et al. (2008), Kühnel (2011))

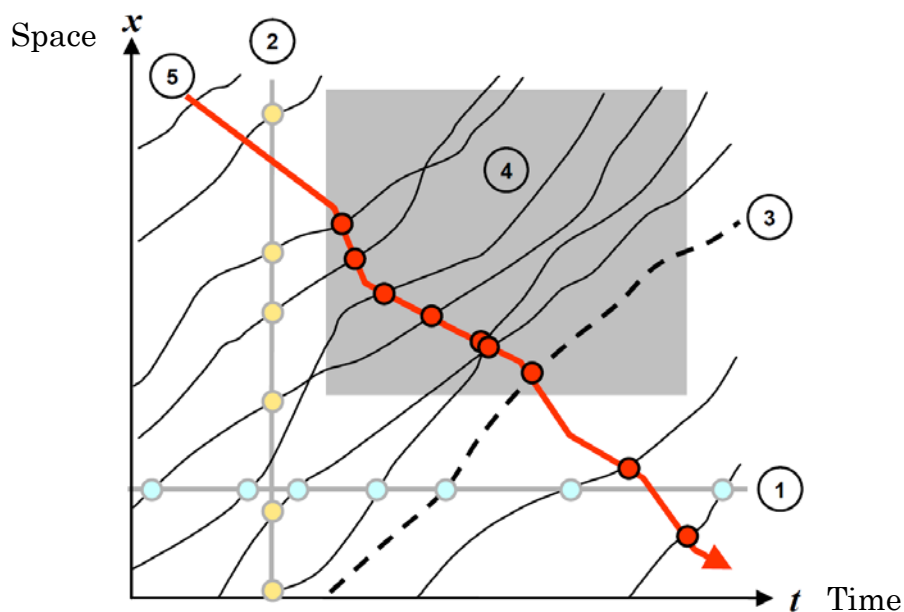


Figure 1: Distance-Time Diagram [from Wolf et al. (2008)]

The increasing spread of information and communication technologies (ICT) enables a third method for traffic data acquisition. This method uses a floating car within the traffic flow (see ③ in Fig. 1) to generate Floating Car Data (FCD). These floating cars serve as mobile traffic sensors by permanently transmitting their current position and speed either to a control centre or other vehicles. This type of traffic data measurements allows the collection of additional vehicular specific parameters, such as travelled path and velocity so that travel times along the examined road sections can be determined. Since FCD only depict the individual course of a journey of a particular equipped vehicle, fusion of data from several FCD vehicles as well as other sources of information is advisable.

2.2 FLOATING CAR OBSERVER

Floating Car Observer allows the automatic observation of oncoming traffic, in order to obtain traffic data (see ⑤ in Fig. 1). Hoyer et al. (2006) introduced the idea of the FCO for the purpose of detecting opposing vehicles on a two-way road by using a travelling public transport vehicle. This is a public transport vehicle that carries a specific sensor system to observe the traffic conditions on the opposite oncoming lane. Thus, the road environment and traffic flows along the public transport route network can be monitored. In Figure 1 the red line depicts the functionality of such a FCO vehicle. Wolf et al. (2008) evaluated different data acquisition strategies to establish a low cost sensing application and decided to use the reflection of an infra-red emitter on number plates to derive information on the speed and the average density of the oncoming traffic. Compared to FCD, the FCO is not part of the observed traffic condition. Therefore, the starting points and the length of traffic congestions on the opposite lane can be determined.

3 BLUETOOTH-BASED FLOATING CAR OBSERVER

3.1 PRINCIPLE

Since every Bluetooth device is uniquely identifiable due to its MAC address, new applications regarding traffic monitoring arose during the last 10 years. Bluetooth devices are available in a number of vehicles (e.g. in terms of mobile devices such as smartphones and headsets as well as in-vehicle systems like satnav or car radio) and thus allows detecting motions of persons and goods (Kasten et al., 2001; Wasson et al., 2008). Besides more and more used stationary Bluetooth traffic detectors, one of these new traffic monitoring applications is the above mentioned approach called DYNAMIC (Ruppe et al., 2012; Gurczik et al., 2012), which was developed by the DLR to combine the advantages of Floating Car Observer with wireless radio-based technologies. DYNAMIC enables the detection of vehicles, pedestrians, cyclists and passengers of public transport carrying Bluetooth equipped devices to collect spatiotemporal traffic data. Since all observations are made indirectly while passing other traffic objects within both the oncoming traffic and the traffic in driving direction, DYNAMIC provides an efficient way to collect traffic information in operational traffic management, as well as for long-term traffic and transportation planning in urban areas.

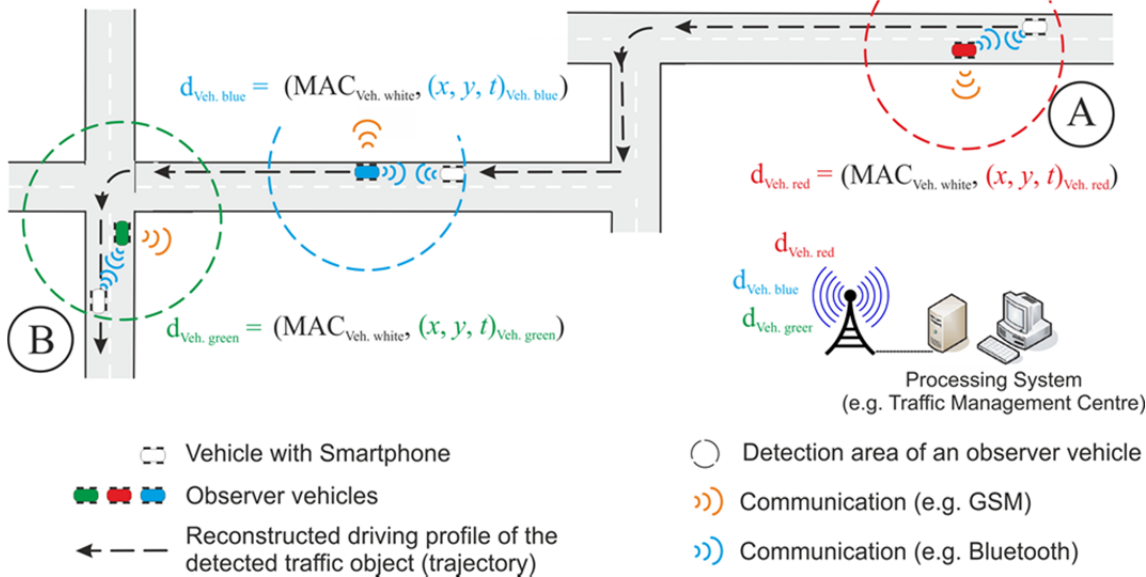


Figure 2: DYNAMIC detection principle [cf. Gurczik et al. (2014)]

3.2 TECHNICAL FEATURES

Bluetooth (Bluetooth, 2004) is a short-range, low-power, IEEE open standard for implementing wireless personal area networks. Bluetooth operates in the globally unlicensed 2.4GHz short-range radio frequency spectrum. Since there is a potential problem of interference from other devices using this frequency band, Bluetooth uses a Frequency Hopping Spread Spectrum (FHSS) scheme, where devices alternate rapidly among 32 available frequencies (divided in two 16 frequencies long trains A and B) to transmit data. To set up an actual connection to exchange the necessary information between two Bluetooth devices, the so called inquiry process is designed to scan for other devices within range and thereby to discover each other. During the *Inquiry Process*, one Bluetooth device (the master) enters the *Inquiry Substate*, whereas the other Bluetooth device (the slave) enters the *Inquiry Scan Substate*. In the *Inquiry Process* the 48-bits unique electronic device address (called MAC) and the internal clock-offset are exchanged in order to set up a lasting connection. With Bluetooth specification version 1.2 or higher a special feature - so called *Interlaced Scan Mode* - was established within the *Inquiry Scan Protocol* for rather powerful Bluetooth devices (e.g. mobile phones) to reduce discovery times.

4 MODELLING MONITORING PROCESS

The device discovery process is modelled as an exponential distribution, that is the number of detections based on Bluetooth is a sequence of independent respectively seen or not seen trials, each of which occurs with a certain probability. This follows from the assumption that the number of vehicles equipped with Bluetooth devices (15% – 20%) and the number of observer vehicles (< 3%) within the network is small, so that the chances to encounter are stochastically independent events. Therefore, the monitoring process can be described as a Poisson process with λ being the average amount of these stochastic incidents and t being the time on the interval $[0,t]$:

$$P_n(t) = e^{-\lambda t} \frac{(\lambda t)^n}{n!}$$

To determine the likelihood that at least a specific amount of events occur within a defined time interval, the certain occurrence probabilities are added:

$$P(t, M \geq m) = 1 - \sum_{j=0}^m e^{-\lambda t} \frac{(\lambda t)^j}{j!}$$

This means that if one is interested, for example, in the determination of origin-destination information, the particular probability to discover a vehicle at its origin respectively at its destination position within the network can be calculated by presuming a certain amount λ of Bluetooth-FCO vehicles and a time interval t (e.g. 1, 5 or 10 minutes). For instance, the probability to obtain a detection within the first minute of the journey of a detectable car is:

$$P(t, M \geq 1) = 1 - e^{-\lambda t}$$

Since the observations on the starting and end points of a journey are stochastically independent events, the probability that both detections occur is equal to the product of all its contributing single probabilities:

$$P(A \cap B) = P(A) \cdot P(B)$$

$$P = P_{start}(t, M \geq 1) \cdot P_{end}(t, M \geq 1)$$

Assuming that the average Bluetooth-FCO traffic volume is 10veh/h, then the single probability to observe a Bluetooth-enabled vehicle within 1min is 15.35%. Thus, the likelihood to detect that vehicle in both the first minute after starting the journey and the last minute before finishing it is only 2%. Figure 3 shows the effect of different observer rates within traffic flow on the occurrence probability of observing an origin-destination pair of values from one detectable vehicle. One can see that for a rate of 1% observer within traffic flow the probability merely increases to 30% only for the longest time interval of 5min.

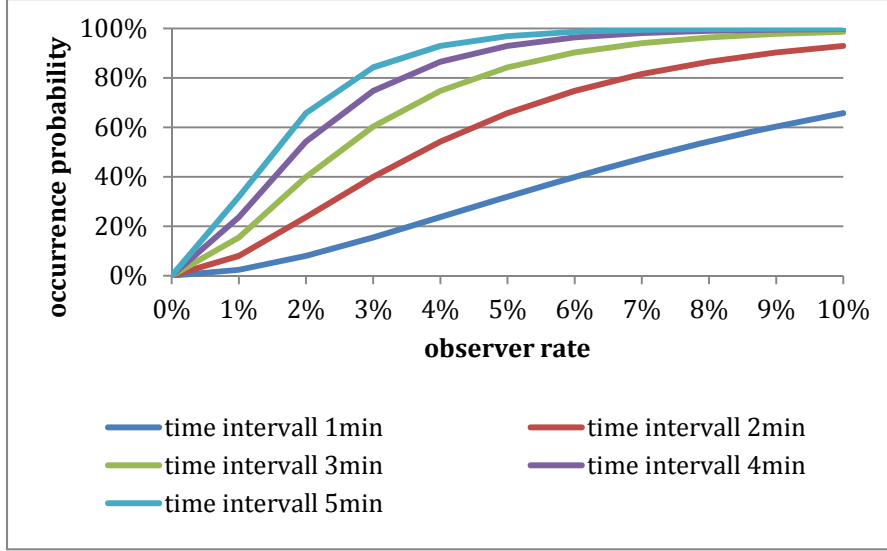


Figure 3: Occurrence probability of at least 1 detection at both starting and ending point of a vehicles journey depending on the observer rate within traffic flow (assumed that traffic volume is 1000veh/h and velocity is 50km/h)

The likelihood above depicts the probability that a Bluetooth-enabled FCO vehicle arrives at a certain cross section of a road segment at a particular time. The particular time is given by the time when a detectable traffic object starts its journey. A second precondition to discover such vehicles refers to the chance that a FCO vehicle and a detectable vehicle encounter each other. To determine the average amount E of encounters on a road segment, the product of the specific traffic densities of Bluetooth-FCO (λ_{Obs}) and of detectable Bluetooth-enabled vehicles (λ_{BT}) as well as the differential speed (Δv) between both vehicles can be used:

$$E_{BFCO} = \lambda_{BT} \cdot \lambda_{Obs} \cdot \Delta v$$

The traffic densities are the products of the overall traffic density (ρ) on the road segment, the number (m) of lanes and the equipment rates either of Bluetooth-enabled vehicles (α_{BT}) or Bluetooth-FCO (α_{Obs}):

$$\begin{aligned} \lambda_{BT} &= \rho \cdot m \cdot \alpha_{BT} & [\text{veh/km}] \\ \lambda_{Obs} &= \rho \cdot m \cdot \alpha_{Obs} & [\text{veh/km}] \end{aligned}$$

Using the fundamental relationship between traffic volume, traffic density and velocity (Greenshields, 1935; FGSV, 2006) the amount of Bluetooth-enabled respectively Bluetooth-FCO vehicles can be derived using the scale basis of one hour. The parameters q_{BT} and q_{Obs} are the specific traffic volumes of these vehicles:

$$\begin{aligned} q_{BT} &= \lambda_{BT} \cdot v & [\text{veh/h}] \\ q_{Obs} &= \lambda_{Obs} \cdot v & [\text{veh/h}] \end{aligned}$$

5 MODEL-BASED EVALUATION

5.1 MICROSCOPIC TRAFFIC SIMULATION

To evaluate the analytical results the simulation environment SUMO (Krajzewicz et al., 2012; SUMO) was extended by the functionality to specify whether a traffic object works as Bluetooth transmitter (traffic objects) or Bluetooth receiver (Bluetooth-FCO). Traffic objects in that case are all the vehicles which can be detected by a detector due to having a Bluetooth device on board. Furthermore, they have no additional functionality. The vehicles which are defined to be detectors are the Bluetooth-based Floating Car Observers used for traffic monitoring. Every simulated vehicle can either be a traffic object, a detector or none of them (i.e. being a pure traffic object with no additional Bluetooth features). To control the Bluetooth detection in SUMO, global parameters like equipment rates for Bluetooth enabled traffic objects and/or Bluetooth-FCO or the detection range can be stated. In Behrisch and Gurczik (2012) different detection models to determine the probability whether a detection took place or not were introduced and a simple exponential approach was realised (cf. the two lower lines in Fig. 4a). The mentioned functionalities were firstly implemented for SUMO version 0.19.0. Based on this first implementation the detection probability distribution function was modified by implementing a new modelling approach including so called *Interlaced Scan Mode* (cf. section 3 and (Gurczik and Behrisch, 2015)) which was released with SUMO version 0.23.0. The results show that the new detection probability distribution function has a much better behaviour concerning the probability of the first detection (cf. coloured upper lines in Fig. 4a), while showing some kind of plateau behaviour when reaching the 90% level as it can be seen in practical results (cf. Fig 5). Since the time needed to observe a detectable vehicle within the detection range does not depend on the traffic demand, the probability functions should not show any deviation between the results of different demands which was retained in both models (cf. Fig. 4a). The underlying simulation scenario was a representation of the Ernst-Ruska-Ufer (abbreviated ERU in the figure below) in Berlin-Adlershof. It includes a total track length of about 4 km with one major road (1.4 km with two directions) and several incoming and outgoing minor roads. It was simulated for a whole day with the demand and route choices being calculated directly from induction loop data. It contains a total demand of about 30,000 vehicles with 4% being trucks and busses. The laboratory results (cf. Fig. 4b) represent stationary Bluetooth detection probability functions derived from using 1 (“1i...”) or 2 (“2i...”) inquirer (observer) to detect a various amount (1, 2, 4, 6) of inquiry scanners (detectable Bluetooth devices) regarding an ideal environment (no disturbances). That research was done to get a ground truth of time intervals needed to detect a Bluetooth device, which is within detection range of an observer.

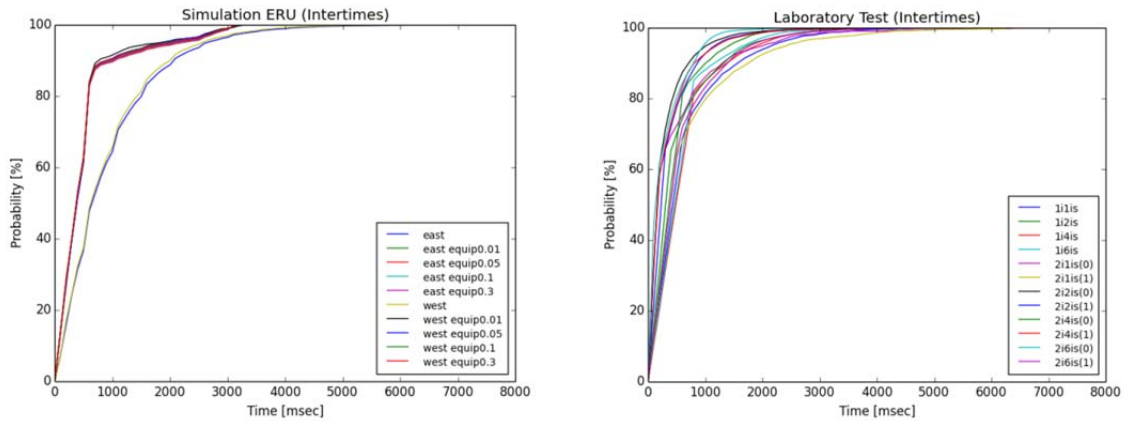


Figure 4: Simulation results from detection process modelling (left, 4a) and laboratory results (right, 4b)

The simulation of the Bluetooth-FCO method enables collecting traffic data, which cannot be easily gathered in real-world traffic monitoring. For example, in a simulation environment it is very easy to derive information on encounters whereas in reality one does not know whether an encounter took place or not if there was no contemporaneous successful detection event. Having a closer look at the times needed to see a detectable vehicle on the road, the average encounter times are much higher on minor streets (cf. Fig. 5), which is not exceptional since encounters are less frequent on that street type due to lower traffic demand. Here, a second simulation scenario was generated to obtain the data from different types of roads. That second scenario represents the so called WISTA area in Berlin Adlershof, which is a road network consisting of 11 major roads (including the first simulation scenario as one of these major roads) and 51 minor roads. The whole scenario has a total track length of 54 km. The number of intersections is 184 with 12 junctions being signalised. It contains a total demand of about 66,000 vehicles within the simulation time period from 00:00 am to 04:00 pm.

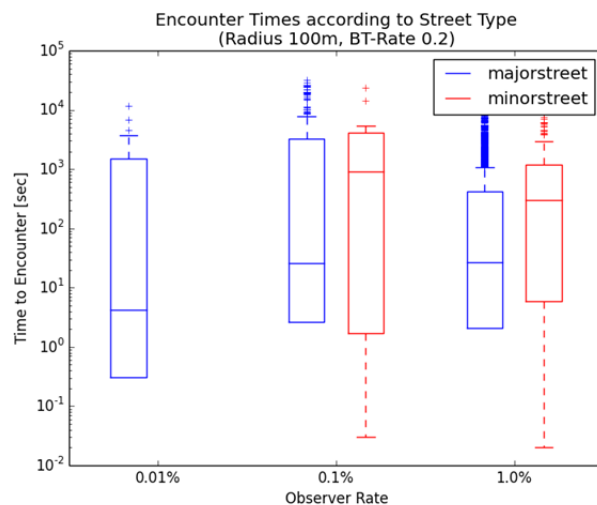


Figure 5: Boxplots showing the average time to encounter according to street type depicted for different observer rates (blue: major streets; red: minor streets)

Beside the encounter times, detection rates (i.e. successful detections per time interval) can be easily analysed as a function of observer rates or overall Bluetooth equipment rates within the simulation. In Figure 6 a two-dimensional histogram depicts the detection rate over all roads (separated into groups of major and minor streets) of the simulated street network for the hours of the day and differentiated for three different observer rates.

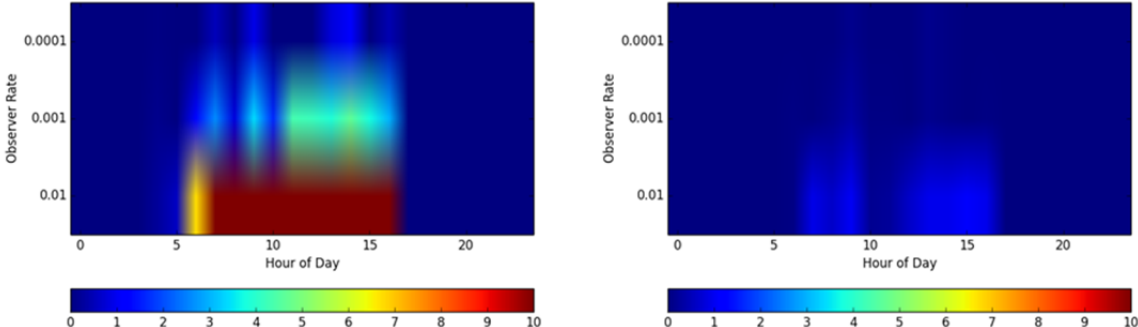


Figure 6: 2D-Histograms showing detection rates aggregated over all roads in the simulation with equipment rate 20% and range 100m (left: only major roads; right: only minor streets)

It is obvious that the detection rates on major streets are fundamentally higher than on the minor streets due to higher traffic volumes and partial stop-overs at street lights where the time to possibly monitor a Bluetooth-enabled vehicle is much higher than during free traffic flow (cf. Fig. 6). One can also recognise that the typical daily time-variation curve is clearly identifiable and that in the early morning and late afternoon hours no detections are made. The influence of different overall Bluetooth equipment rates is depicted in Figure 7 for a certain street within the simulation network.

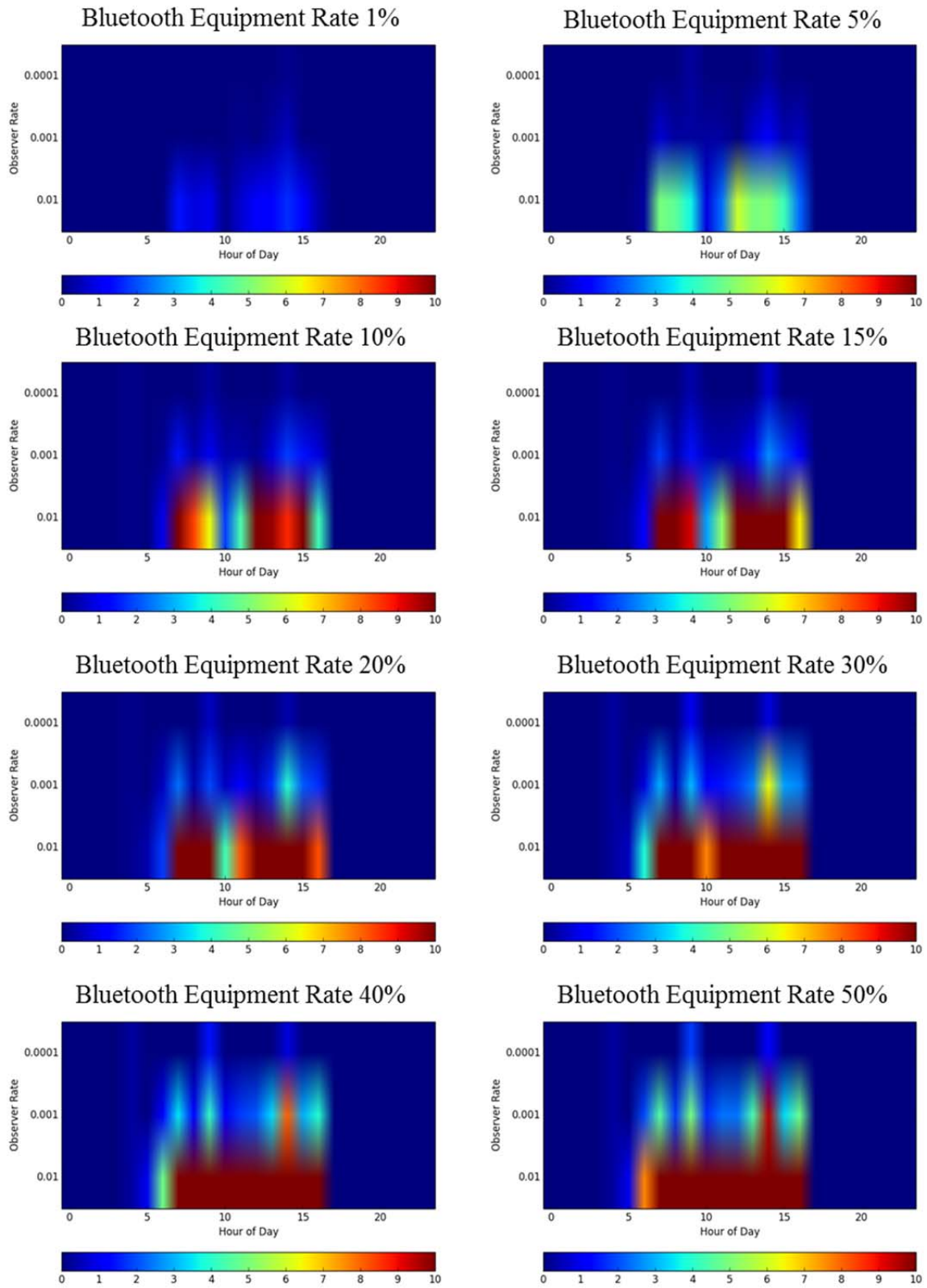


Figure 7: 2D-Histograms showing detection rates aggregated over one specific road in the simulation network for different rates of Bluetooth-enabled vehicles (Ernst-Ruska-Ufer)

5.2 FIELD MEASUREMENTS

To evaluate how the monitoring process is influenced from real environment several test runs with 8 moving observers using multimodal Bluetooth-enabled traffic objects (cars, pedestrians and cyclists) were conducted. The field test took place during August 2013 from 9 a.m. to 10 a.m. and 1 p.m. to 3 p.m. on the roads of the WISTA area in Berlin-Adlershof / Germany (cf. Figure 8). The observers moved freely according to their desired speed respectively to local feasibility and under consideration of the German Road Traffic Act (StVO). The floating observers were simultaneously considered as ordinary Bluetooth-enabled traffic participants, which should be detected. That means, the observers had to monitor each other in order to derive traffic data. Within the observer cars and on the bicycles a prototyped DLR Bluetooth monitoring system was installed whereas the pedestrians used smartphones with a specific application to realise the detection process.

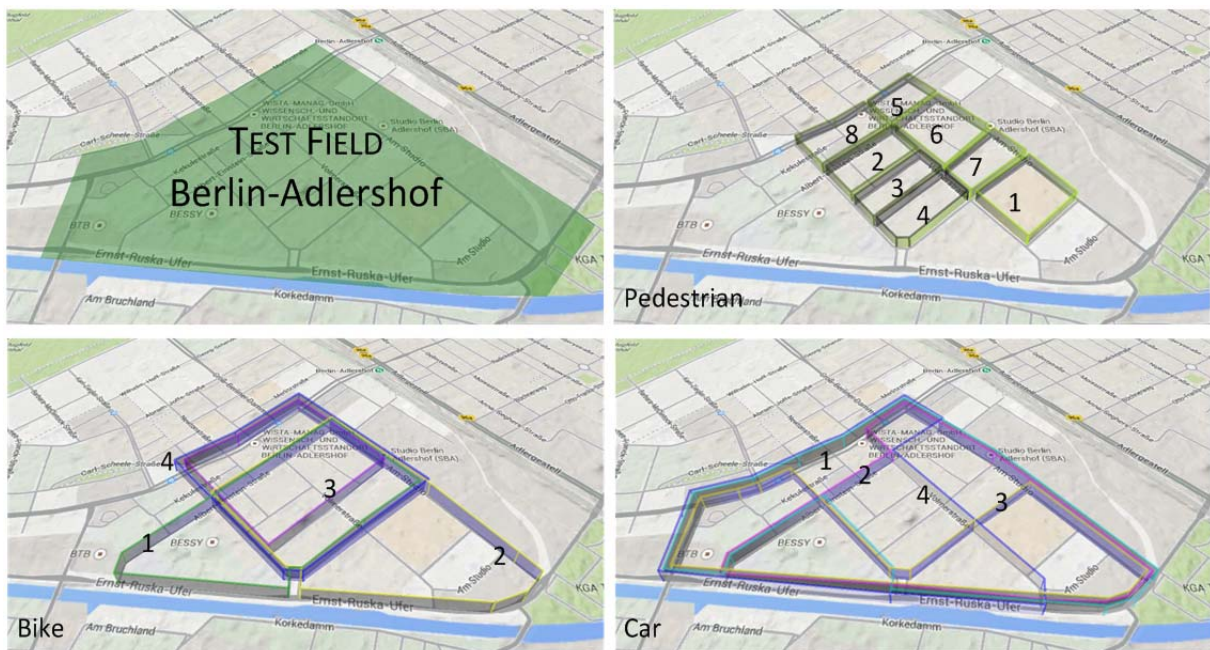


Figure 8: Test field WISTA area in Berlin-Adlershof / Germany.

Looking at the time it took a Bluetooth-FCO to detect other Bluetooth-enabled traffic objects, the probabilities of a successful detection process within certain time intervals can be determined (cf. Figure 9). In the upper chart of Figure 9 one can see a comparison of different test methods. To be more exact, these are the results from a stationary test run under ideal laboratory conditions ('labor'), two more stationary test runs ('ERU_ost' and 'ERU_west') in the field and finally the aggregated DYNAMIC results from two test runs of the above mentioned field test. The DYNAMIC results for each of both test runs are separately depicted in the lower charts of Figure 9. Note that in these field tests observer car 3 (red line) had some major problems in collecting data.

The results in form of probability distribution functions indicate a quite good similarity between the simulation model and the real-world detection behaviour (cf. also Gurczik and Behrisch, 2015) so that the simulation model can be used to examine some more complex and rather resource intensive test scenarios, which are not feasible in economic terms.

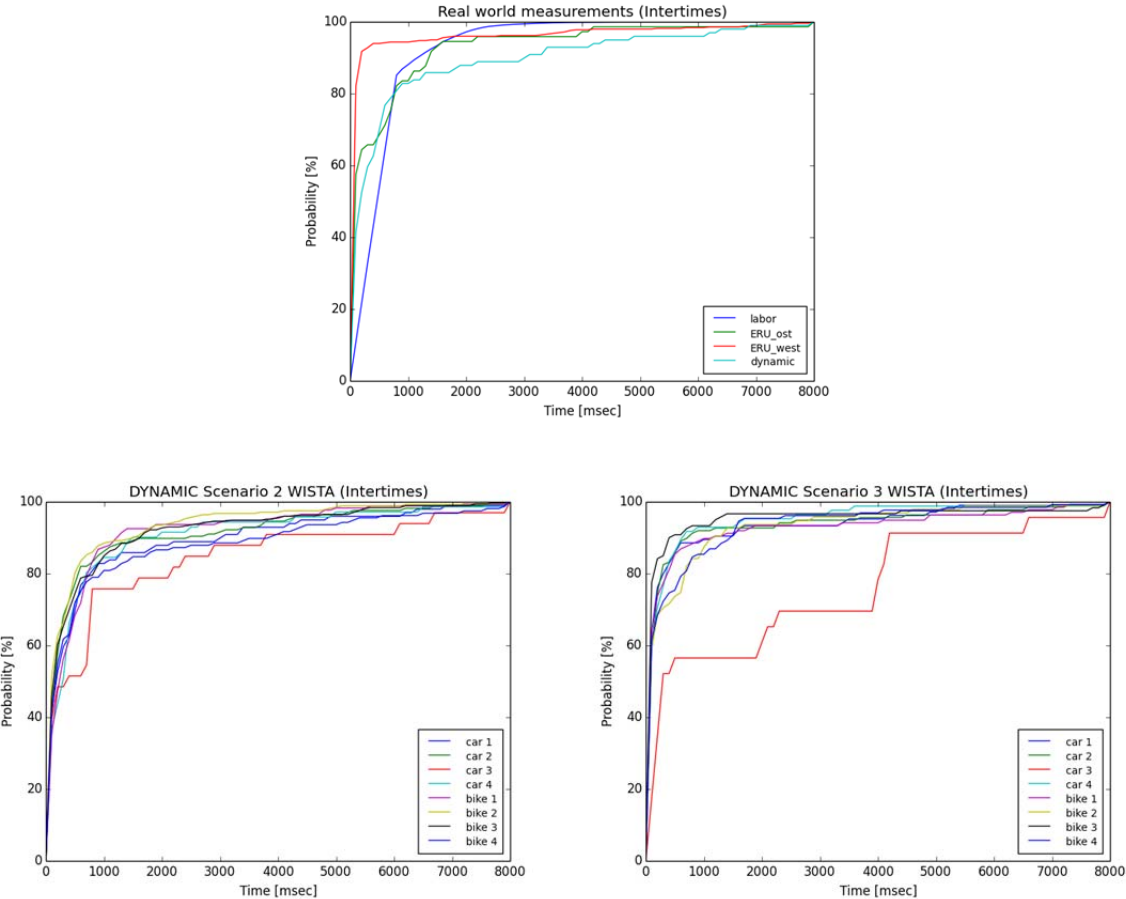


Figure 9: Field test results according to the detection probability within a certain time interval

6 CONCLUSION AND FUTURE PROSPECTS

This paper depicts a Bluetooth-enabled Floating Car Observer approach to monitor Bluetooth-enabled traffic participants, in order to generate real-time spatiotemporal traffic data in a road network. By using Bluetooth as sensing module traffic objects such as vehicles, cyclists, pedestrians which are equipped with Bluetooth-enabled devices can be observed. Due to the specific Bluetooth connection establishment behaviour a Bluetooth-enabled device can be recognised on every point within the road network by using its unique identifier address. Hence, particularly desired traffic information such as origin-destination information can be derived.

A major drawback of that kind of traffic monitoring is the prediction of the likelihood of a (re)-detection of such a Bluetooth-enabled traffic object. Since Bluetooth has a specific detection range and a complex connection establishment process, it is not clear, how long it takes to detect a device and where that device was exactly recognised within detection range.

This paper tries to answer this question by introducing a theoretical model to describe the detection process as an exponential distribution and to determine its specific properties such as the encounter rate of Bluetooth-FCO and detectable traffic objects. To evaluate the analytical model, simulations as well as laboratory and field experiments with Bluetooth observers and detectable Bluetooth devices were conducted to measure detection rates as a function of encounter times.

The results indicate a good similarity between the field measurements and the simulation model results. Still the probability distributions look different enough to require some further adaptations of the parameters. Since broader field test (e.g. with a higher amount of observing vehicles) are difficult to conduct due to economic reasons, the simulation offers a wide range of possible (further) research studies, including:

- Observing density - this is how many observer cars are in a specific road segment during a certain time interval,
- Observer distribution in the network – in this simulation observers moved freely along the roadside but what is about a fleet which might cover specific roads permanently,
- Quality of traffic information – is the quality and quantity of traffic data generated from Bluetooth-FCO sufficient to gain high quality traffic information such as travel times, velocities or lost time in case of traffic incidents.

Answering these questions will be subject to further research.

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