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A practical analysis of communication characteristics for mobile and distributed pollution measurements on the road

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Summary

Measuring environmental data in city areas has become an important issue for municipalities due to several climate directives. As fixed measuring stations are inflexible, cost-intensive, and limited to monitoring a specific spot, we developed a distributed environmental monitoring network called Environmental Monitoring in Metropolitan Areas (EMMA). This architecture is based on the delay tolerant networking approach and can be integrated into existing Public Transportation Networks (PTNs). Buses or other vehicles can be equipped with sensor nodes that gather data and forward messages. In order to evaluate the basic ideas of this project we performed a series of real-world experiments. Besides analyzing the behavior of 802.11-based Wireless Local Area Network (WLAN) between moving vehicles in a controlled environment, we also evaluated the communication performance in urban environments. Moreover, we examined the qualification of a Disruption Tolerant Networking (DTN) implementation for spreading measurement results throughout the network. The suitability of EMMA's architecture has been successfully demonstrated by these experiments. Copyright © 2007 John Wiley & Sons, Ltd.

KEY WORDS: environmental monitoring; Disruption Tolerant Networks; Car2X Communication; public transport; performance evaluation

1. Motivation

Air pollution has become a serious issue for the world climate. Extreme weather conditions obviously occur more often in various regions all over the world. Agreements like the Kyoto Protocol [1] as well as different national or European directives [2–5] aim at reducing the emissions of certain pollutants. Thus, especially in densely populated metropolitan areas mechanisms are needed for determining the current level of air pollution in specific districts. Unfortunately, the operation of a large number of fixed measurement stations is very expensive.

The Environmental Monitoring in Metropolitan Areas (EMMA) project proposes a communication architecture that can be integrated into existing Public Transportation Networks (PTNs) to allow area wide pollution measurements. The sensor nodes can be installed in buses or trams where they continuously measure the environment. The collected data has to be centrally aggregated in order to analyze the air quality in the city or in specific districts. A simple approach would be to use an available infrastructure network such as General Packet Radio Service (GPRS) or Universal Mobile Telecommunications System (UMTS). However, due to the permanent data exchange

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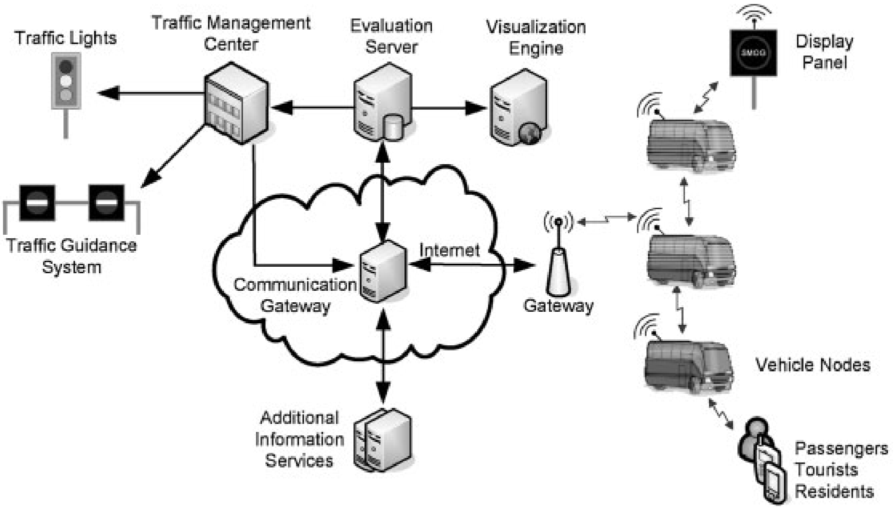

Fig. 1. Basic architecture of EMMA.

and, hence, the incurred high costs, the total operational costs would likely prohibit the introduction of such a system. We decided to base our system on a decentralized approach using a self-organizing *ad hoc* network. Sensor nodes may share information whenever two buses meet and thereby spread information throughout the whole PTN. It is possible to forward the measured data to a central server or external network *via* one or more gateways which may be installed at major bus and train stops. This way it is possible to establish a cost-efficient dynamic traffic management system that considers up-to-date information on current pollution instead of relying on mathematical models that extrapolate from the data measured by only a few fixed measurement stations. In addition, each bus may be equipped with a passenger information system that combines the measurements of several buses and thus provides information on the local situation to people that might be sensitive to specific pollutants. Of course, the distributed architecture is not limited to exchanging measurement data but may also be used for the spreading announcements or other information that can be used in passenger information systems.

Communication in highly dynamic environments puts high demands on the network protocols being used. Especially in Vehicular Ad Hoc Networks (VANETs) nodes move at high speeds and links change frequently. This problem is addressed in the field of Disruption Tolerant Networking (DTN) [6]. The DTN Research Group (DTNRG) proposed a DTN protocol that enables the dissemination of information within a network in which nodes only meet sporadically [7].

In this paper we introduce the requirements for establishing a mobile and distributed measurement network and present the architecture of EMMA. Afterwards, we discuss the results of several test runs for evaluating the real-world communication performance of WLAN and DTN in vehicular environments in order to analyze the feasibility of our approach.

2. System Architecture

Various parameters affect the dissemination time of datasets throughout the network, such as the area covered by the PTN and the frequency of buses serving a given route. Figure 1 shows EMMA's architecture elements, which can be structured in two groups: the elements forming the delay tolerant network (mainly DTN nodes in different configurations) and the elements connected by a regular Wide Area Network (WAN) (traffic management and control). Each node comprises a wireless network interface, a DTN service, and some data storage capacity. Sensor nodes are additionally equipped with sensors (e.g., NO_x), a Global Positioning System (GPS) receiver, and an optional vehicle interface. Plain DTN nodes act as mobile relays to speed up data distribution.

Besides vehicle mounted nodes, there may also be two types of stationary DTN nodes: gateways and smart display panels. A gateway connects the DTN to the traffic management WAN and therefore is best installed at a central location, for example, a main intersection. The gateway receives messages (so-called bundles) from the DTN and forwards the measurement results to the evaluation server *via* a WAN connection. It also forwards messages (e.g., control messages for traffic management devices or information displays) from the WAN to the DTN. Smart display panels are the

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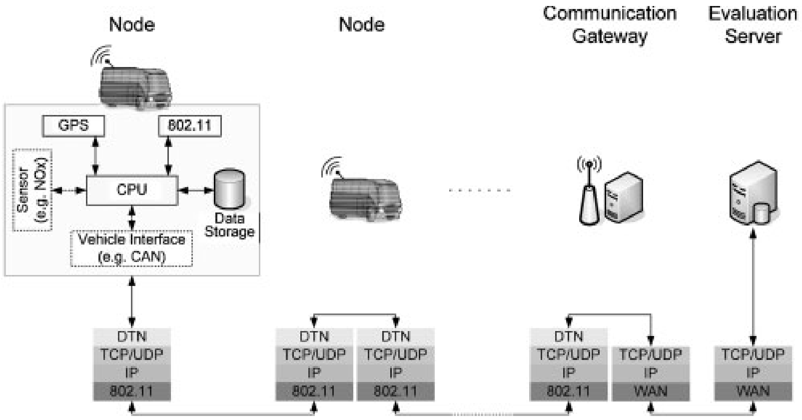


Fig. 2. The EMMA protocol stack.

second type of stationary nodes. These displays show information on current pollutant concentrations. The measurement results are gathered from passing vehicles and computed autonomously by the panel. Further, the display may also receive messages from a control center (*via* the DTN) in order to show, for example, traffic information. Displays also act as relays, speeding up the bundle distribution process at no additional cost.

EMMA's WAN-side elements are the communication gateway, the Central Evaluation Server (CES), and the visualization engine. The communication gateway connects EMMA's various subsystems with each other and the Internet, and provides an interface for the integration of additional information services (e.g., electronic tourist guides). It also translates DTN bundles to regular Transmission Control Protocol (TCP) streams and *vice versa* (Figure 2). The CES is the final sink of all measurement data originating from the DTN. It comprises a database and a set of rules to trigger events based on the computed pollutant concentration of certain areas. An example for such an event is sending a signal to the traffic management center if the particulate matter threshold is exceeded. The traffic management center, already installed in most major towns, controls the traffic flow with traffic lights and guidance systems. On receiving a signal from the evaluation server, the traffic management center can either reduce the traffic load in polluted areas or even entirely close down certain roads for specific vehicles (e.g., trucks or cars without catalytic converters). The visualization engine generates a human readable city map with an overlay of the pollutant concentration from the evaluation server's database. A web-interface (using Google Maps [8]) provides the map along with area-specific information to citizens. Furthermore, such maps are powerful tools for traffic flow and land-use planning.

One of the main ideas behind EMMA is to provide an inexpensive system. Thus, we decided to stick to off-the-shelf components as far as possible. Since the EMMA software runs on any standard Linux system a small-scale-PC/104 fits all the requirements. The costs of a node including the small-scale-PC, a Differential Global Positioning System (DGPS) receiver, an Personal Computer Memory Card International Association (Wireless Local Area Network) PCMCIA (WLAN) card with external antenna, a weather proof enclosing, and a power adapter sum up to roughly 450 EUR. Not included is the custom sensor that depends on the specific area of operation.

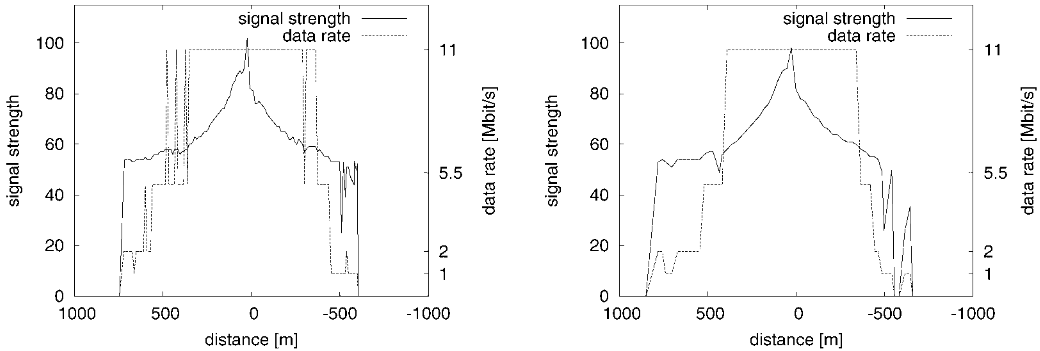
3. Practical Performance Evaluation

For evaluating EMMA's applicability and performance in real-world scenarios, we implemented a prototype system based on off-the-shelf notebooks. These prototypes are only intended to demonstrate the principles of future operation. The notebooks are equipped with an 802.11b WLAN PC Card, a low cost omni-directional WLAN antenna with 3 m cable extension, and an Universal Serial Bus (Global Positioning System) USB (GPS) receiver supporting DGPS for higher accuracy. To obtain environmental data for this demonstration we used a temperature sensor attached to the serial port of the notebook. The prototypes have been installed in vehicles, with the external antenna being placed in front of the vehicle's roof. Our road test of EMMA comprises three scenarios to asses the main aspects of the communication performance in vehicular environments: the connectivity while two vehicles pass each other (A), the connectivity in urban scenarios (B) as well as the message delivery in vehicular DTNs (C). The setup of these three scenarios is described in the following. In scenario A, we analyzed the behavior of 802.11b WLAN with two vehicles driving past each other for determining the maximum communication range and the communication characteristics. For these measurements, we chose a straight, secluded road on the outskirts of the city of Braunschweig. The road section has a length of 1200 m and is lined with trees along one side. The road was not used by other vehicles during our measurements. It is mostly planar with only a small depressed area near the middle of the driving distance. All in all, the environment made it possible to obtain comparable results of different measurement runs, since dynamic influences of, for example, other vehicles or obstacles are minimized. The same setup was used in scenario B, for analyzing the performance of message delivery between two vehicles. Finally, in scenario C we also investigated the performance of 802.11b WLAN with two vehicles exchanging messages in a residential area in Braunschweig. This area is characterized by a grid-like road topology. It is covered with multi-story apartment houses that prevent a direct line-of-sight between two parallel road sections. Moreover, cars were parked along the street, pedestrians walked on the sidewalk and vehicles drove through the streets. Due to the multitude of varying parameters, these tests are not reproducible and can only give an impression of the qualification of 802.11b WLAN in urban scenarios. A special tool ('gpsping') was developed to help us collect useful data in our scenarios. This way we are able to determine the signal strength and data rate of each received packet as well as the vehicle's position at that time. In the following, we present the results of our practical evaluation in detail.

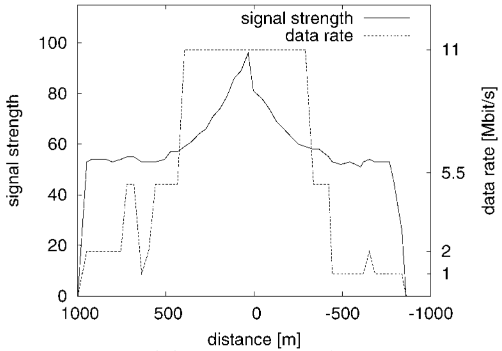
3.1. Analysis of 802.11b Signal Strength and Data Rate

The main focus of scenario A was the behavior of 802.11b WLAN in scenarios with high mobility. Special attention was turned on how long two vehicles driving past each other are able to exchange data. To measure the signal strength and the WLAN data rate we equipped two cars with laptops, WLAN cards, external antennas, and GPS receivers. Each of these laptops ran an instance of 'gpsping'.

Figure 3(a)–(c) shows the measurements with two vehicles driving past each other at a speed of (a) 20 km/h, (b) 50 km/h, and (c) 80 km/h. The graphs are normalized to the distance between the vehicles for comparing the characteristics of signal strength and

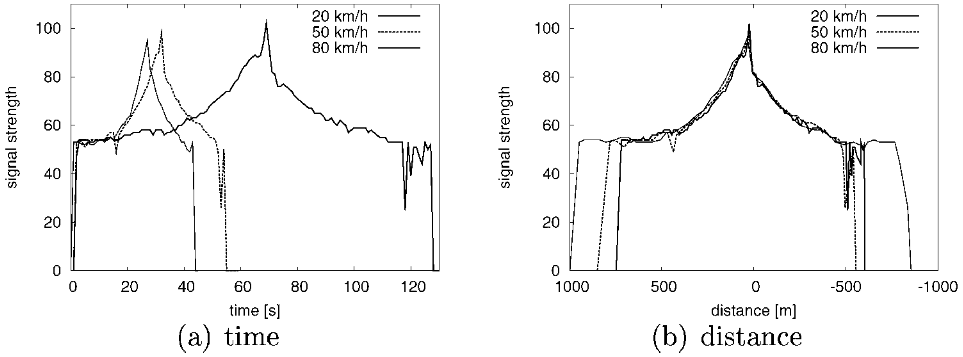


(a) v=20 km/h (b) v=50 km/h



(c) v=80 km/h

Fig. 3. 802.11 performance at different vehicle speeds.



(a) time (b) distance

Fig. 4. Comparison of signal strengths at different speeds.

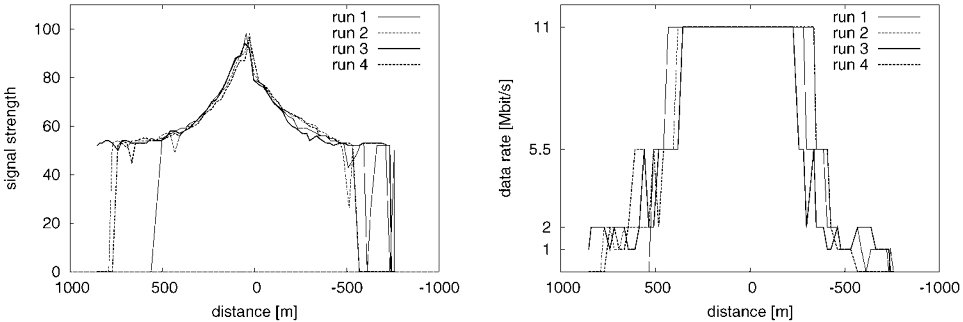
data rate at different vehicle speeds. At the beginning of a measurement run, the vehicles are positioned at opposite ends of the road, at the maximum distance of 1200 m. During the measurement, the vehicles pass each other. This point corresponds to a distance of almost zero in the graph. A negative distance value means that the vehicles have already passed each other. The distance is computed on the basis of the vehicles' position and the high precision time signal, which are both obtained from the GPS receiver. The GPS position update rate is 1 Hz, and for this reason the resolution of the measurements depends on the vehicle speed. Therefore the 20 km/h measurement run has four times the resolution of the 80 km/h measurement run. As a side effect the WLAN data rate appears to fluctuate more heavily at 20 km/h.

In Figure 3(a) it can be observed that the range is well above 500 m. Both range and the signal strength are slightly asymmetric because the antennas are mounted at the front side of the vehicle's roof, which causes a shadowing effect on its rear side. The signal strength graphs in Figure 3(a)–(c) show a characteristic uniform peak when both vehicles meet. During all measurement runs at a specific speed the maximum WLAN data rate is available for a continuous period of time, with durations of 61 s at 20 km/h, 28 s at 50 km/h, and 17 s at 80 km/h. For each run there is also a period of time in which the link operates at a lower data rate but is still available for transmissions. This period is roughly as long as the period of full data rate.

Figure 4 illustrates the signal strength at different speeds. Figure 4(a) gives a good impression of the durations of the measurements. The signal strength graph in Figure 4(b) is normalized to distance and shows how similar the peaks are even at different speeds. In Figure 5 it can be observed that the results of different measurement runs at the same speed are reproducible.

The probability distribution of the WLAN data rate in dependence of the distance is shown in Figure 6. It is calculated on the basis of all measurements. For distances of <333 m the probability for a data rate of 11 Mbps is 92 %. It decreases to 57 % for distances of <666 m, 47 % for distances below 1000 m, respectively. It should be mentioned that distances below 202 m always resulted in 11 Mbps links in all measurement runs.

The probability distribution of the signal strength is depicted in Figure 7. Figure 7(a) shows the distribution of the signal strength for distances lower than 333 m.



(a) signal strength (b) data rate

Fig. 5. Comparison of measurements at the same vehicle speed.

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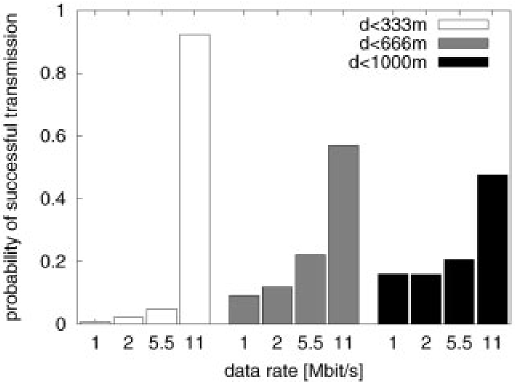


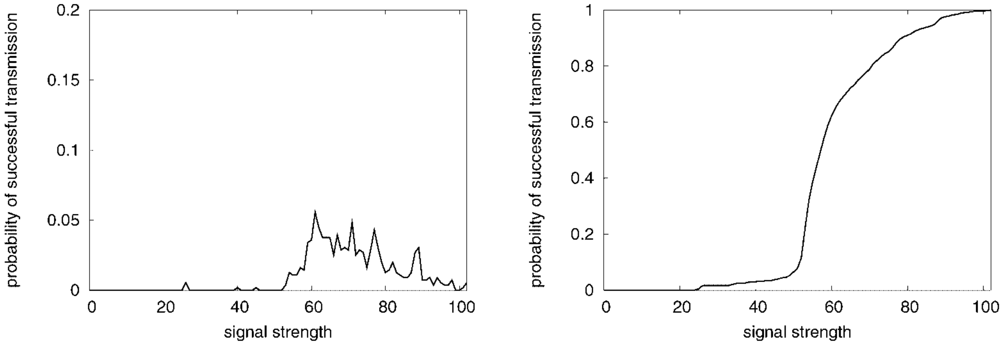
Fig. 6. Probability distribution of 802.11 data rate.

It can clearly be seen that the measured signal rate at this distance is mainly higher than 60 which means that the connection between the vehicles is very stable and transmissions can take place at high data rates. Hardly any lower values have been measured in our scenario, which results from packets that were lost due to transmission errors during the measurement. Figure 7(b) shows the cumulative probability distribution for the whole drive-by scenario. The graph illustrates that while both vehicles pass each other, most of the signal strength values are in an interval of 50 and 65. At signal strengths lower than 24 no connection is possible.

3.2. Experiences with 802.11b Range in Urban Scenarios

A second field of interest was the transmission range of 802.11b WLAN in an urban environment (scenario B). The results of this scenario are of major importance for the usability of WLAN hardware for EMMA. To gather some real-life data we equipped two cars with the same hardware components mentioned above and drove through a densely settled residential area in Braunschweig.

Figure 8(a)–(d) illustrates exemplary traces of the two cars while driving through the city. The arrows point in the driving direction while the dots indicate that a WLAN link is available between the two nodes. The link status was probed once a second. At the beginning, both vehicles start at the same place and head towards the first intersection where the vehicles' routes split up (Figure 8(a)). After one vehicle turned right at the first intersection, the direct line-of-sight was lost. However, the WLAN link remains available for 8 s. The transmission range is about 100 m at this intersection. The same effect can be observed at the next intersection. A connection can be established about 7 s and 118 m before both vehicles meet. While passing this intersection, the vehicles were able to exchange data during a period of 16 s (Figure 8(b)). Thereby, a data rate of 11 Mbit/s was available for 13 s even without having a direct line-of-sight during the whole period of time. At the next intersection the vehicles can communicate over a distance of 231 m along the same road section. Figure 8(c) illustrates that the vehicles stay connected for about 30 s (with short disruptions) although the direct line-of-sight is interrupted by a row of multi-story buildings. A further connection between the vehicles becomes available for about 5 s when both pass the next intersection at the same time. The intermittent connectivity after both vehicles passed the intersection can be explained by multi-path propagation effects as well as vacant lots. Finally, Figure 8(d) gives an impression of the WLAN transmission range along straight roads. The connection is established even before the vehicles arrive at the intersection and lasts for about 40 s. The maximum transmission range was 171 m.



(a) d≤333 m (b) cumulative propability d<1000 m

Fig. 7. Probability distribution of the signal strength.

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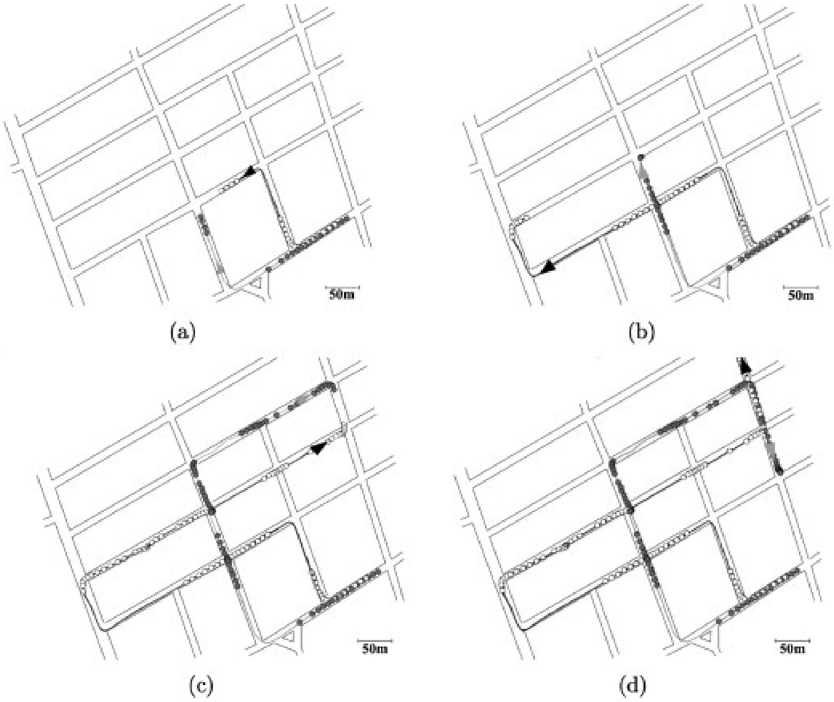

Fig. 8. WLAN connectivity in urban scenarios.

In summary it can be stated that the results in the urban scenario clearly differ from the results obtained on the secluded road outside the city with respect to the transmission range and thus to the duration of the connection. However, this is not unexpected since the radio propagation in built-up city areas is highly affected by dynamic changes in the environment like other road users. Nevertheless, the results show that WLAN is feasible for deploying DTN approaches like EMMA even in urban scenarios. The vehicles were able to exchange information at the maximum data rate of 11 Mbit/s during almost the whole connection period. This is due to the fact that the signal strength increases faster than in the scenario on the secluded street when both vehicles get into transmission range. The signal attenuation mainly results from multi-path propagation effects and not from the physical distance of the vehicles. In this scenario, vehicles were able to exchange data over distances of more than 100 m, even without direct line-of-sight. Of course, we do not expect these results to be representative for urban areas in general. However, our measurements have been performed in a very challenging environment. Since bus or tram routes often follow main roads, we can assume that in these scenarios the outcome may be even more encouraging. All in all, the results are promising for realizing EMMA in urban areas. Moreover they can be used in order to optimize DTN mechanisms and communication protocols during future work.

3.3. DTN Measurements

In the previous scenarios, we focused on the performance of 802.11b WLAN in urban vehicular scenarios. Although these results are very encouraging, they do not prove the suitability of DTN in general and the DTN reference implementation in particular to set up a distributed measurement network. To investigate this in more detail we equipped two measurement vehicles with the adequate software and performed tests on the same secluded road. Two vehicles were passing by each other while exchanging bundles. Figure 9 shows some exemplary results of this measurements for vehicle speeds of 20 km/h (a) and 50 km/h (b). The number of exchanged bundles is aggregated in 10 s intervals. As expected the number of exchanged bundles increases with the signal strength. At a speed of 20 km/h it was possible to exchange 3545 bundles during a period of 150 s. At 50 km/h the connection lasted for 60 s which was enough time to transfer 1943 bundles. The resulting average data rates of 1087 Byte/s at 20 km/h and 1455 Bytes/s at 50 km/h are clearly lower than it could be expected on the basis of the previous measurements, possibly due to the development stadium of the

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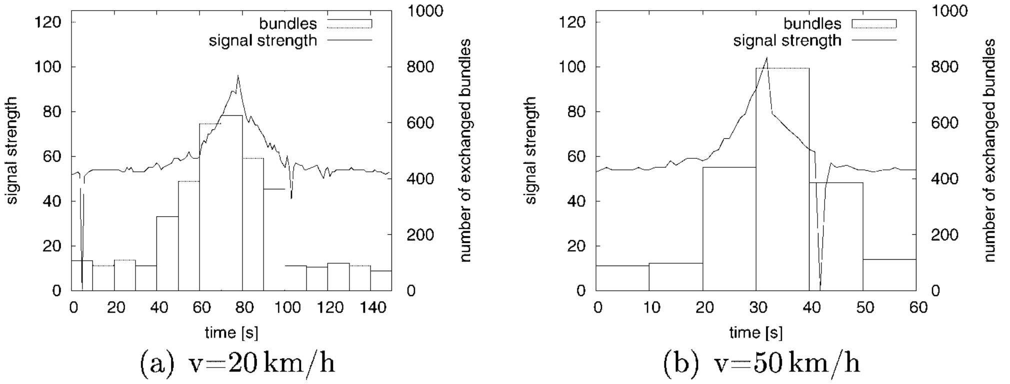

(a) v=20 km/h (b) v=50 km/h

Fig. 9. DTN bundle exchange at different speeds.

DTN reference implementation. We observed that the reference implementation handles the bundle exchange in a rather inefficient way. It sends a burst of bundles and then starts to look for other potential communication partners within range. For small bundles this behavior wastes a lot of performance since links in vehicular environments persist only for a short period of time.

To explore the usability of DTN for a distributed measurement network we set up four test vehicles each equipped with a WLAN enabled notebook running the DTN software. One node acted as the CES being placed at one side of our test site. The other three nodes obtained sample data. One of them acted as a stationary node at the far end of the test site outside the CES' range. The remaining two acted as mobile nodes driving predefined routes on the test site with a size of 400 m × 500 m. In Figure 10 you can see the time it takes to transfer a new bundle to the CES. The average delay of bundles created by the stationary node is 26.28 s, the minimum is 1.77 s, and the maximum is 226.79 s. The fairly low minimum is caused by a mobile node directly relaying between the stationary node and the CES. The average delay of bundles created by the two mobile nodes is 7.44 s, the minimum is 1.47 s, and the maximum is 75.45 s. This evaluation proves the basic idea behind EMMA to be working but the performance of the DTN reference implementation is not yet sufficient. The implementation does not seem to efficiently handle a huge number of small bundles thus further protocol optimizations will be necessary for enhanced applications.

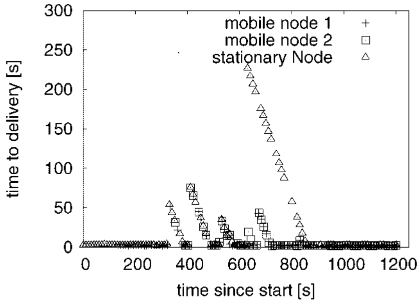

Fig. 10. Delay of bundles created by different nodes.

3.4. Discussion of the Results

The field tests were set up to determine whether 802.11 WLAN satisfies EMMA's requirements regarding wireless communication techniques. The transmission range and the data rate were evaluated on a secluded road. Our results show that a transmission range of more than 500 m is feasible using standard hardware components. The measured value is based on the assumption that a direct line-of-sight is available. In the urban scenario, we found out that communication is still possible over a distance of more than 100 m even if no direct line-of-sight is available. The comparison of various result sets has shown that the measured values were reliably reproducible. Finally, we analyzed the feasibility of DTN-based message delivery for our application.

The evaluation results are very encouraging, since they clearly show that the net data rate of 802.11b WLAN is high enough to exchange more than 200 000 result sets while driving past each other at the speed of common overground public transportation vehicles. While the performance of the experimental DTN implementation does not yet suffice to operate at full WLAN capacity, we have seen that the system already works well in urban environments.

4. Related Work

The DTN approach used by EMMA is based on a general architecture for delay tolerant communication proposed in Reference [6]. Previous work in this area deals

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with various routing mechanisms for data delivery or different applications of DTNs. The UMassDieselNet project [9] is closely related to EMMA. In this project, 40 buses were fitted with off-the-shelf communication hardware for evaluating the performance of bus-to-bus and bus-to-infrastructure communication. The buses send location information as well as measured data to a central server whenever Internet access is available. Although several aspects of DieselNet are comparable to EMMA, it is not a distributed information system where measured data is spread through the network. Since both projects have different application scenarios, requirements on the communication performance differ as well. An interesting part of the DieselNet infrastructure is throwboxes [10] that are intended to increase the network connectivity and relay data. These relays may also be helpful for EMMA in order to ensure the data exchange between bus lines that meet infrequently. Our work is also related to ferry-based networks [11–13]. This research area aims at connecting nodes in sparse networks by using robots, buses, or other vehicles for asynchronous data transport. In the DakNet project [14], such networks are used to provide Internet access to remote villages in India and Cambodia. However, the requirements of ferry-based networks differ from EMMA since data is only exchanged at specific access points and delay is limited to the travel time between a village and the Internet gateway. Other related work in the area of DTN include [15,16]. The communication performance of vehicle-to-infrastructure communication has been studied in References [17–19]. In contrast to our work, they do not analyze characteristics like signal strength and data rate over the distance of two moving vehicles. Additionally, the performance of DTN bundle exchange in urban environments has not been evaluated in previous work.

5. Conclusion

Environmental monitoring and traffic management are important tasks in times of increasing traffic densities and environmental pollution. Several regulations have been enacted to reduce air pollution. They demand additional efforts monitoring several pollutants in the air. The measurement data has to be collected, documented, and provided to the public.

Instead of using a few fixed measuring stations, a mobile and distributed sensor network can be used to gather area wide measurements of the air pollution. Most larger cities have dense overground PTNs and thus are well suited for our approach. The communication architecture presented in this paper provides the basis for implementing such a distributed system. EMMA can provide a cost-effective alternative to other environmental monitoring systems especially as it is fast and easy to set up and gets by with only a few fixed infrastructure components. Using the DTN approach, measurement data is spread throughout the network to a CES that analyzes and combines the incoming data. Local evaluation of sensor data by the nodes or intelligent display panels along main streets is also possible. The architecture is based on standard 802.11 WLAN technology, so basically any public WLAN hotspot can be used to forward measured data to the evaluation server. People who are sensitive to specific pollutants could receive current information directly from one of the network components (e.g., a bus, gateway, or display panel) by using a mobile WLAN-enabled device. EMMA could be integrated in a flexible traffic management system that allows for a selective guidance of traffic flows taking environmental parameters into account.

The evaluation results showed that 802.11b WLAN is well suited for communication between sensor nodes attached to public transportation vehicles in a city. By using external antennas it is possible to extend the range of the network far enough to have a fair amount of time to exchange data with two vehicles driving past each other. The DTN concept works as expected and thus is usable to complete our architecture.

The purpose of EMMA is not only limited to implementing a distributed measurement system. The Internet gateways may also be used to offer several information services. A passenger information system using the EMMA architecture may, for example, include the distribution of news or special announcements of current events in the city. When vehicle-to-vehicle communication is introduced to the mass market, equipped vehicles may also benefit from the information services provided by EMMA.

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Lars C. Wolf received the diploma degree in 1991 and the doctoral degree in 1995, both in Computer Science. From 1991 to 1996 he worked at IBM's European Networking Center in Heidelberg, Germany, on multimedia transport, resource management, quality of service, media servers and multimedia applications. In 1996 he joined the Technical University of Darmstadt as Assistant Professor. There he led a research group working on multimedia networking and quality of service in distributed multimedia systems. He joined Universität Karlsruhe (TH), Germany in 1999 where he was Associated Professor in the Computer Science Department and Alternate Director of the Computer Center. Since spring 2002 Lars Wolf is Full Professor for Computer Science at the Technische Universität Braunschweig where he is head of the Institute of Operating Systems and Computer Networks. His current research interests include network and system support for multimedia, mobile communication, *ad hoc* networks, multi-player games. He serves on editorial boards of international journals. He has served as chair and member of program committees of many international conferences and workshops.

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