Mobile and Distributed Measurement of Air Pollution in Metropolitain Areas Using Car2X Techniques

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Abstract. In the last years, the measurement of environmental data in city areas has become an important issue to municipalities due to several national, European and even international climate directives. However, stationary measuring stations are inflexible, cost-intensive and limited to monitoring environmental data in distinct key areas. In this paper we present a decentralized architecture for environmental monitoring in metropolitan areas using Car2X communication techniques. This architecture, called EMMA, can be integrated in e.g. existing public transportation networks by equipping buses with sensor nodes that communicate with each other. Thus, the system is able to obtain area-wide measurements that are distributed within the ad-hoc network. A central visualization engine is used to analyze and publish the measured data and therefore allows to react to high pollution levels by e.g. closing streets for trucks. A field test revealed that the idea behind EMMA and the soft- and hardware used to realize our prototype implementation works as designed and is ready for more advanced testing like a large-scale field deployment.

1 Motivation

Measuring environmental data like particulate matter, ozone, CO_x or NO_x-emissions is an important task in most modern societies. Densely populated areas need constant monitoring of environmental conditions to assure the citizen's health as well as compliance with political directives. Each sensor can only analyze its immediate surroundings and thus a complete coverage of the whole metropolitan area is very difficult and expensive. So usually only some key spots are monitored.

In this paper we describe a new way to approach this problem. EMMA (Environmental Monitoring in Metropolitan Areas) is a mobile and distributed system which provides almost complete coverage of the whole metropolitan area with sensorial data in an easy to implement and cost effective way. It uses an existing conventional network such as the public transportation system to send mobile sensor nodes to all residential areas. By doing this, a relatively small number of sensors is sufficient and hardly any data network infrastructure is needed as the sensor nodes spread their data all by themselves. The whole system is self-organizing and thus requires little to no setup efforts. Whenever a node discovers another node within its transmission range both start the data exchange process. Beginning with the newest set of measured data each node sends all stored information to every other node within range. This makes EMMA an inexpensive and flexible solution that is easy to implement.

EMMA takes advantage of e.g. existing public transportation networks or taxi fleets in a city. The measurement nodes can be installed in e.g. several buses, trams or taxis in order to obtain almost well-distributed pollution measurement from all parts of a city. This idea leads to lower costs because it is not necessary to create and maintain any kind of infrastructure used in common environmental monitoring systems. EMMA consists of a number of independent nodes equipped with specialized environmental sensors, a (D)GPS receiver and a WLAN transceiver. The sensor permanently measures data, the node combines this data with GPS positioning information and a timestamp and queues this set of information for transmission. Our prototype nodes use temperature sensors in order to obtain dummy data for demonstration purposes, since our work focuses on the Car2X networking architecture and its feasibility. The development of sensors and transducers for relevant environmental data is not in the scope of this publication.

Most public transportation systems have one or only a very few “central” points where many lines meet. These points are excellent locations for central “gateways” to a central evaluation server and the traffic management center. Our architecture also includes smart display panels. These panels collect and process data from all passing public transportation vehicles in order to show information on the air pollution in the local area (e.g. notifications to ozone-sensitive citizens). They may also be used to redirect traffic flows in conjunction with traffic guidance systems.

The remainder of this paper is organized as follows: At first, we introduce the requirements of our distributed monitoring system and describe the technologies and basic mechanisms that are involved. Afterwards, the system architecture is presented in section 3. In section 4 some results of an experimental evaluation are shown. Finally, the paper is concluded in section 5 and an outlook on future work is given.

2 Background

The idea of EMMA is based on the subproject “Dynamisches Schadstoffkataster” [1] of the German INFO-REGIO project that has been carried out in the run-up to the world fair EXPO 2000. The project’s goal was to develop a new sustainable and efficient traffic management for Greater Braunschweig. During the project it has been shown that the approach of monitoring environmental data on moving vehicles is feasible and a sensor prototype was developed. Nevertheless, the project was not fully realized because of problems with the communication infrastructure and the subproject dealing with the installation of a central traffic guidance center in Braunschweig. It was planed to use the existing private mobile radio of the local public transportation carrier. However, the project members realized very quickly that the bandwidth of this private mobile radio is not sufficient to transfer the additional measurement information. At the end of the project, two options for realizing the data exchange remained. One the one hand, the measured data might be transmitted via cellular radio networks at high operating costs. This possibility was used for the system's prototype. On the other hand, the project partners proposed to install a separate private mobile radio system that is dedicated to the exchange of measured data. However, this solution would lead to high investment costs.

At this point EMMA comes into play. In this project we take up the intermediate results of the INFO-REGIO project and combine them with new approaches of distributed mobile ad-hoc networks on the basis of Car2X communication and disruption tolerance. Several requirements have to be met in order to realize a robust distributed measurement system. Most importantly it has to be affordable even to small cities. For this reason inexpensive off-the-shelf components should be used whenever possible. To lower the costs of operating EMMA even further, it has to be easy to maintain and administrate but for all that remain flexible and disruption tolerant.

The measurement results can be used to adjust traffic flows in the case of high air pollution in specific areas. Moreover, this information can also be provided to the public as required by European directives like e.g. [2–5]. For this, a visualization component is necessary to make it easily accessible to residents as well as to visitors of a city. This can be realized e.g. via Internet services, display panels or novel mobile information systems using e.g. mobile phones or PDAs. Thus, people who are sensitive to specific pollutants can easily get informed about the current situation. Since EMMA has been designed to be a mobile and distributed system for information dissemination, it's application range is not limited to gathering and providing information about air pollution. Equipped vehicles may also be used as passenger information system, provide up-to-date information about events in a city or display area maps to tourists. This way it is possible to extend the existing public transportation system to a metropolitan information system that is able to cover a city area very well.

EMMA utilizes Car2X communication in order to transport the measurement results to the control center where the data is processed and visualized. However, only some of the public transportation vehicles might carry sensors with radio interfaces and therefore the nodes are not distributed densely enough to establish a traditional ad-hoc multihop network with continuous end-to-end connectivity. In fact, it has to be expected that communication is not possible most of the time, since the radio range is limited and there are only a few nodes in a large area. Nevertheless, there are rare and very brief periods of time (some few seconds) in which two passing vehicles are within each others radio range and consequently are able to exchange measurement data. Eventually each of those two vehicles will pass other vehicles, exchanging data again.

EMMA's data transport mechanism takes advantage of this periodic data exchange in a store-and-forward manner. However, it is not possible to apply traditional end-to-end delivery since there are no end-to-end routes in such a highly fragmented mobile network. A recent approach to this problem is the Delay-Tolerant Network (DTN) Architecture [6] and the corresponding reference implementation [7]. Both are currently developed by the "Delay Tolerant Networking Research Group". In a DTN, so called bundles (the protocol data units of a DTN) are forwarded from node to node whenever a connection is available. Apart from the non-existent end-to-end route, the main difference between a DTN and a conventional packet switched network is the persistent storage of PDUs. A DTN node is able to cache a bundle as long as no appropriate connection is available, and to forward it to another node much later.

A routing strategy is required in order to deliver a specific bundle to its destination by constantly choosing the "right" next node. There are two routing approaches which are especially interesting for the EMMA scenario. Firstly, the predetermined nature of public transportation networks - both the roadmaps and the schedules are known in advance - may be used to derive an optimal route for each bundle. However, this leads to a loss of flexibility since a single failed transmission or a slight delay in the schedule requires the recalculation of the whole route or else would result in a significant negative impact on the routing performance. The second mechanism is to forward a bundle to each node in range which has not yet received the bundle. These nodes then also start forwarding the bundle, thereby "flooding" the whole network. This process is also known as epidemic routing and continues until the bundle is finally delivered to its destination node. A drawback is the increased amount of bundles that each node has to store, since a specific bundle has to be cached on multiple nodes until it reaches its destination. The removal of delivered bundles from the network also requires additional control messages. However, flooding is a very attractive routing mechanism for highly dynamic environments since it does not rely on any externally provided network information and therefore obsoletes any routing administration. This means that a system based on flooding is very flexible and robust, since it is able to adapt to nearly any scenario without manual adjustments. EMMA's architecture uses these advantages and implements mechanisms to avoid performance problems due to the greedy requirements of flooding with regard to storage capacity and bandwidth. Traffic prioritization ensures the preferred delivery of important data (e.g. significantly changed ozone values) and a time-out scheme is used to remove old bundles from a node's cache if it runs short of storage capacity. The most recent measurement results are then transmitted with a higher priority. This scheme is based on the assumption that the most recent data has a higher value than older data.

The system's performance is further enhanceable by adding optional architectural entities: relays and gateways. Relays are stationary nodes with high storage capacity and serve the purpose to speed up the flooding process and to smooth out load peaks. Consequently, relays are installed in heavily frequented places such as main intersections. Gateways are also stationary, but are equipped with a regular Internet connection besides the wireless DTN interface. They improve the performance by providing a shortcut to the control center, thereby increasing the network's bandwidth and decreasing the amount of time needed to deliver measurement data to the control center. Like relays, gateways should be installed at heavily frequented places. However, for cost reasons it is preferable to use existing Internet connections such as public or municipal hotspots, or the WLAN already installed in the public transport company's premises. EMMA's flexible architecture takes these economic considerations into account, therefore a gateway may be placed anywhere in the transportation network as long as it is regularly passed by mobile nodes.

3 System Architecture

The system architecture of EMMA has to face several challenges. There are a couple of parameters that affect the average dissemination time of a given dataset through the network, such as the area covered by the public transport network and the frequency of buses serving a given route. In addition, delayed buses may also affect the connectivity in the network e.g. if specific buses do not meet each other. This is why EMMA is based on the DTN approach mentioned above.

Figure 1 shows the integration of the DTN into EMMA's architecture. It is inserted as an additional abstraction layer between the application and the transport layer, thereby allowing the application to pass messages to the DTN layer, which handles all tasks needed to establish reliable communication over constantly appearing and disappearing links. Whenever a message is passed to the DTN layer, it is wrapped into a DTN protocol data unit (also called a bundle). Depending on the availability of a suiting link, the bundle is either stored (until a link becomes available) or transmitted to another node. Besides exchanging messages with local applications, the DTN service also exchanges bundles with other nodes' DTN services, thereby implementing routing in a store-and-forward manner. Whenever a link suiting the current routing strategy is available, the DTN abstraction layer pulls stored bundles from its cache and transmits them via regular TCP to the correspondent node. No modifications to the protocol stack below the DTN layer are necessary, since this is just a regular end-to-end TCP/IP transmission between both nodes' DTN layers. On the other node, the bundle is received by the DTN service and either delivered to an application (if the node is the bundle's destination) or stored for later delivery to yet another node.

Figure 2 shows EMMA's architecture elements, which can be structured in two groups: the elements forming the delay tolerant Car2X network (mainly DTN nodes in different configurations) and the elements connected by a regular WAN, which mainly serves traffic management and control purposes. The nodes' common features are a wireless network interface and a DTN service, including some data storage capacity. Those nodes mounted on vehicles to perform measurements are additionally equipped with sensors (e.g. NO_x), a GPS receiver and an optional vehicle interface. There are also vehicles which are only equipped with plain DTN-nodes, lacking the ability to perform measurements. It should be noted that this option is intended for applications which require very expensive sensors. In this scenario only a few vehicles measure pollutants, while the other vehicles are needed as communication relays to ensure a fast distribution of the measurement data. However, the use of the DTN is not necessarily limited to the transport of measurement results. Once installed, such a network could be used for many other applications, such as telemetry, in-vehicle passenger information systems, or even updating (in-vehicle or external) advertisement displays.

Besides vehicle mounted mobile nodes, there are also three types of stationary nodes belonging to the DTN. These are gateways, relays and smart display panels.

A gateway connects the DTN to the traffic management WAN and therefore is best installed at a central location, e.g. a main intersection, so that many mobile nodes pass through the coverage area of the gateway's wireless interface. The gateway then receives 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. Although only one gateway is mandatory, EMMA's architecture supports multiple gateways, which may be installed to increase the bandwidth of the DTN in order to provide future location based services such as electronic tourist guides or other mobile information systems.

The second type of stationary nodes are relays, which boost the DTN's performance by reducing the bundle delivery time. Like gateways, relays are installed at central locations, but are not connected to the WAN. Relays enable the exchange of bundles between vehicles which drive on the same route and direction, but at a distance exceeding the nodes' transmission range. Further, relays at central intersections are passed by vehicles of different lines, thereby preventing network fragmentation and speeding up the bundle distribution process.

Smart display panels are the third type of stationary nodes. These displays show information on the current pollutant concentration, which is of interest to the area's inhabitants and to people who are especially sensitive to certain pollutants (e.g. ozone). 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 e.g. traffic information. It should be noted that displays can also act as relays at no additional costs, since they already comprise the required hardware.

EMMA's WAN-side elements are the communication gateway, the central evaluation server and the visualization engine. The communication gateway connects EMMA's various subsystems with each other and the Internet, and provides an interface for the integrations of additional information services (e.g. electronic tourist guides). As shown in figure 2, it also translates DTN bundles to regular TCP streams and vice versa.

The central evaluation server is the final sink of all measurement data originating from the DTN. It comprises a database and a set of rules in order to trigger events based on the computed pollutant concentration of certain areas. An example for such an event is triggering a signal to the traffic management center if the particulate matter threshold is exceeded.

The traffic management center, which is most probably already installed in most major towns, controls the traffic flow by traffic lights and guidance systems. On receiving a signal from the evaluation server, the traffic management center can either reduce the traffic load in the polluted areas or even entirely close certain roads for certain types of vehicles (e.g. trucks or cars without catalytic converters).

The visualization engine creates a human readable city map with an overlay of the pollutant concentration. For this purpose the required measurement data is obtained from the evaluation server's database. A web-interface provides the map along with area-specific information to citizens. Furthermore, such maps are powerful tools for traffic-flow and land-use planing.

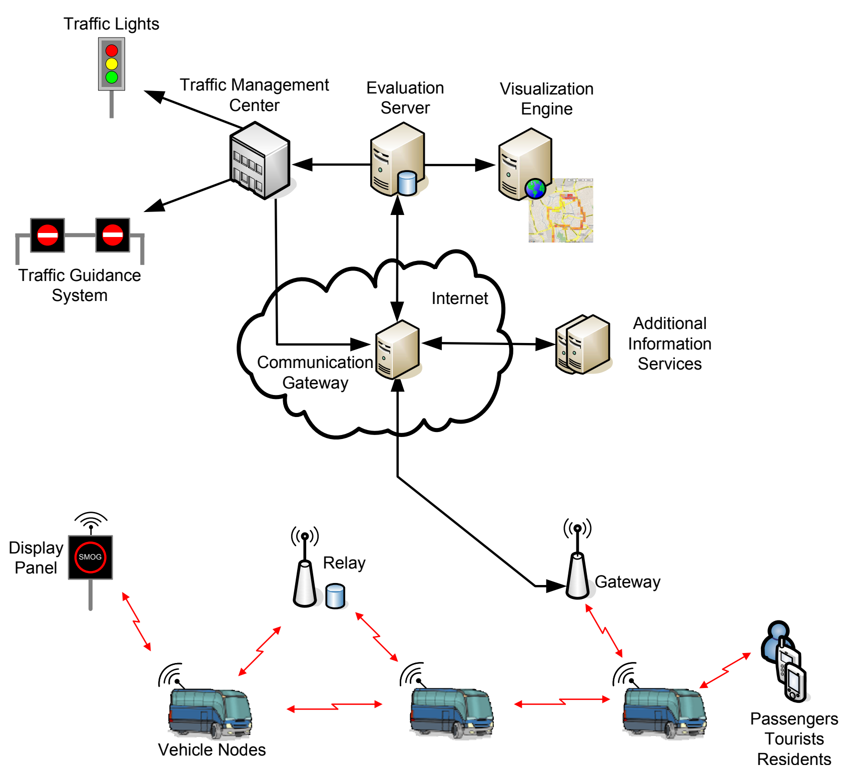


Fig. 1. Basic architecture of EMMA

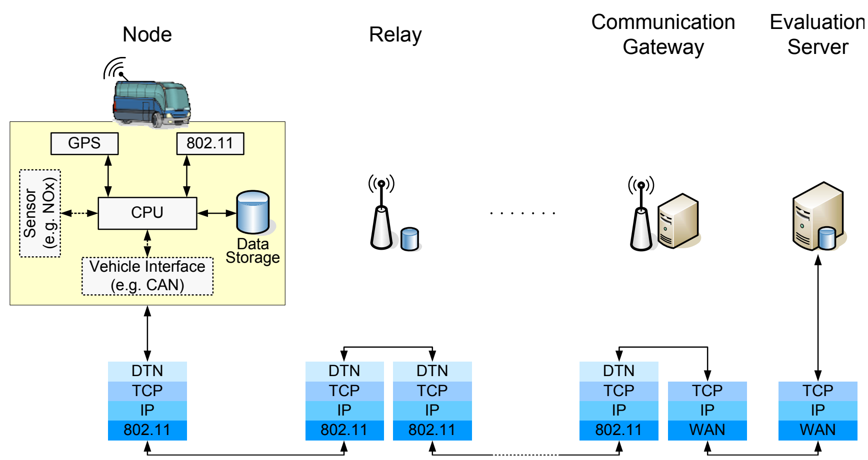


Fig. 2. The EMMA protocol stack

3.1 Visualization Engine

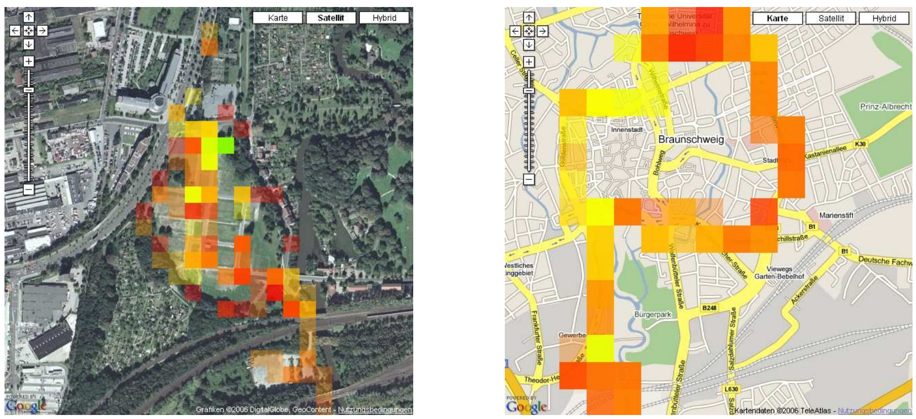
There is a multitude of ways to analyze and interpret the data collected by EMMA nodes. The visualization engine's task is to aggregate this data and prepare it in a fashion that allows the key implications to be understood intuitively.

As a lot of information in this data is location specific it is especially useful to chart it on a map. That way it is easy to get a global overview but also have location specific details. For this sample application we decided to use the google maps service [8] since it is easily customizable and widely available.

This sample visualization engine consists of three tiers. In the back end we have a MySQL database holding the measurement data extracted from the central evaluation server. Whenever new data becomes available it is immediately inserted into the database with at least the timestamp and the geographical coordinates of the dataset as well as the measured value, which in our example case is a temperature value. The middle tier consists of a PHP script that resides on the server and which is invoked by the client application with a couple of parameters. Subsequently, the script retrieves the appropriate information from the database, processes it and returns it to the client as an XML document. The front end is an HTML page that presents the map and a dialog which allows the user to configure what data is shown in what way. We decided to divide the visible area in a grid like fashion where each of the tiles represents the combined measurements of that region, since previous work has shown that the representation of each single measurement is not practical. The data aggregation can be done by the server residing second tier, which not only speeds up the data display but also reduces network traffic.

The actual value for each tile, i.e. the average of the measurements in that region, is represented by the tiles color, where red stands for the lowest (single) value, yellow for the overall average value and green for the highest (single) value in the database. Optionally a second characteristic of that tile can be represented by its opacity. In this sample application the opacity depends on the number of measurements that took place in that region.

The granularity of data aggregation, i.e. the number of tiles the map is split into, can be configured from the client side, allowing the user to find the trade off between speed and accuracy that suits his needs best. The user can also decide about the maximum age of data to be taken into account, thus discarding measurements that happened a long time ago and might not be of interest anymore.



(a) Local (b) Global

Fig. 3. Different views of an exemplary test ride

The client application polls the server application in a user definable time interval for new data and updates the map if necessary allowing a quasi realtime analysis of gathered information. Additionally the map is also updated whenever the user moves the map or changes the zoom level. The granularity is always relative to the current map excerpt which means that zooming in raises the granularity allowing for a more detailed view on the data.

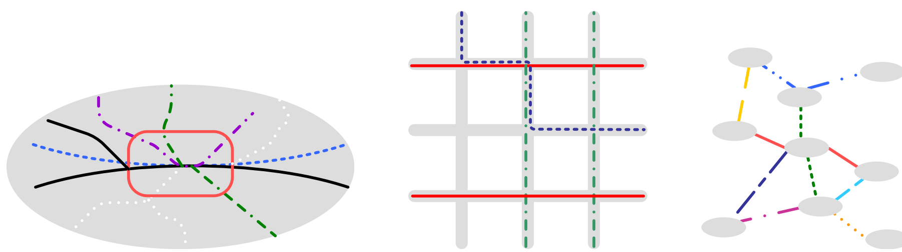
3.2 Hardware Platform

EMMA's main idea is to provide a cost effective and inexpensive distributed environmental monitoring system. To achieve this goal we decided to stick to off-the-shelf components as far as possible. Our software runs on any standard Linux platform and thus there is a wide collection of devices available to use for EMMA. The devices do need some kind of 802.11 WLAN interface to communicate with other nodes, gateways or relays. Of major importance is some kind of external and weather proof antenna to extend the range of the WLAN. Also at least one USB port is needed to connect a (D)GPS receiver to the device. Since GPS is not very accurate in determining the current position of the vehicle, a DGPS receiver which is able to receive differential GPS signals is recommended. If no such receiver is available any standard USB GPS receiver will work with EMMA but the accuracy is possibly not sufficient. The specific sensor to obtain the desired environmental data may be connected to the device by any interface that is available. Please keep in mind that you might have to customize the EMMA software to support devices that are not connected via the serial port. In addition to these interfaces the measurement units have to be weather proof and shock resistant. The power supply should be compatible to the voltage usually used in public transportation vehicles. All these requirements in mind we chose standard off-the-shelf laptops to build some early development prototypes of the EMMA sensor nodes. Those prototypes are just proof-of-concept devices and cannot be mounted on a common bus. They consist of a laptop, a PCMCIA WLAN card, a serial temperature sensor, a USB GPS receiver, a car power adapter and an external WLAN antenna. Since this setup is neither weather proof nor shock resistant we do not recommend using this kind of hardware in a final version of EMMA. One possible solution to this problem is to use a small-scale-PC/104 system [9]. It is equipped with a 300 MHz CPU and 256 MB of memory. It provides serial and USB ports and PCMCIA slots for our WLAN card. It has low power consumption and uses a shock resistant compact flash card as mass storage device. It is able to run a standard Linux system. To lower the costs of one node even further it might be better to chose off-the-shelf access points which run embedded Linux (e.g. OpenWrt [10]). These WLAN access points are equipped with an ARM CPU, up to 64 MB RAM, an USB host and a serial interface. Standard flash USB sticks can be used to store up to 8 GB of data and the WLAN hardware is already integrated into the system. External antennas are available, as well as cross compilation utilities to build the needed tools on any PC based Linux platform. The computing power of these access points is high enough to satisfy the needs of EMMA and the DTN software, the storage capacity is extendable through more flash USB sticks. To extend EMMA's ability of communicating with passengers of the public transportation vehicles it might be interesting to attach Bluetooth adapters to the sensor nodes. In order to do this USB Bluetooth adapters should be used, since USB is available in any of the above stated configurations.

The costs of a node including access point, DGPS receiver, external WLAN antenna, weather proof enclosing and the needed power supply sum up to roughly 300 EUR. Not included is the custom sensor that depends on the specific area of operation.

3.3 Integration into Public Transportation Networks

For evaluating whether the proposed architecture can be integrated into typical public transportation networks (PTNs), we analyzed the bus and tram networks of different cities. We found out that most of these networks can be classified into three main categories as shown in figure 4. The PTNs of smaller or mid-sized cities like e.g. Braunschweig often have a very centralized infrastructure. The main station is located in most cases either in the inner city and/or next to the main railway station. The network itself represents a star-like topology, where most bus lines meet at the main station. Additional ring lines may exist as well in this category of PTNs. Another topology that can be found especially in e.g. North American cities where streets are set out like a chessboard (e.g. several districts of New York City). In these cities, bus lines often simply follow this grid structure (e.g. one line from North to South and another line from East to West). This network structure leads to a quite equal coverage of the city area. Finally, large cities like e.g. Berlin or New York City as a whole mostly have a quite decentralized PTN topology. The city is structured in several areas like e.g. the city districts. The topology of the bus network within these areas corresponds to previous topologies. Further bus lines interconnect the different areas with each other.



(a) Star (b) Grid (c) Decentral

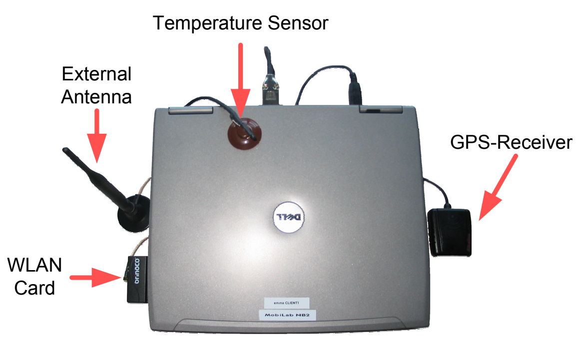
Fig. 4. Different topologies of PTNs

The way of integrating the EMMA infrastructure in PTNs of the first category is quite straightforward. The gateway will be placed at the main station where most bus lines meet. Additional relays might be placed in some distance to the main station where e.g. ring lines that do not run through the main station meet other bus lines. In order to accelerate the data dissemination, additional relays or even gateways might be installed at some specific places depending on the real bus network and schedule. This approach is also suitable for networks of the third category, whereas each area should probably have its own gateway to the communication server. Areas that are interconnected with a high service frequency may share a common gateway. Having a grid-like PTN topology is probably the most challenging scenario for installing the EMMA infrastructure with less efforts. The best location for a gateway clearly depends on the specific characteristics of the PTN as well as the bus lines that should be equipped with sensor nodes. It might probably make sense to place the gateway at a point where orthogonal lines meet. This way e.g. buses or trams running from east to west may collect the data of several other lines running from north to south.

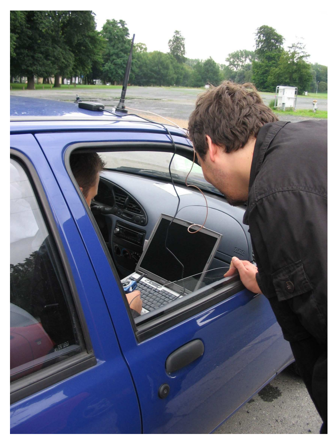
In this case several relays might be necessary depending on the schedules. Another possibility would be to place gateways at the termini if several lines meet there. However the optimal number and location of infrastructure components depends clearly on the specific city. All in all it can be stated that EMMA can be integrated into most PTNs with a low number of stationary infrastructure components. The decentralized architecture makes its possible to spread information directly between vehicles. At specific points additional relays or even gateways may be needed to improve the network connectivity and the dissemination time of messages through the network.

4 Experimental Evaluation

For analyzing the performance of the proposed architecture, we implemented a prototype system and evaluated the communication performance between the vehicles in a practical road test. This prototype is shown in figure 5(a). It consists of a notebook, an 802.11b WLAN PC Card, a low cost omnidirectional WLAN antenna and a GPS-Receiver that supports DGPS for higher accuracy. Moreover, we used a temperature sensor for demonstrating the collection of measurement data. Figure 5(b) displays the installation of such a prototype node into a vehicle for the road test. All in all four of such nodes were involved in the test, whereby one of the nodes modeled the communication gateway and the evaluation server.



(a) EMMA node



(b) Node Installation

Fig. 5. EMMA prototype node

Our first concern was about the general behavior of 802.11 in vehicular city environments. An important question was how long the transmission range between two moving vehicles is and thus how long these two vehicles are connected with each other. Therefore we implemented "gpsping", a tool enabling us to record not only if another node is within wireless range but also the current position of the node. To achieve this we used a patched orinoco kernel driver module which includes the signal strength and the current transmission rate of the wireless connection into each received packet. "gpsping" takes this information and combines it with accurate information about the current position and time acquired by a GPS receiver. These results are written to a logfile for later evaluation. In a scenario with two computers mounted on a moving car, both running "gpsping", it is possible to combine the data collected by each one of them to get a complete coverage of the wireless reception. This specific aspect has been evaluated in a free-space and a residential area scenario. A second aspect that has been analyzed is the performance of disseminating measurement data using the DTN protocol. In the following, we present the results of our experimental evaluation in detail.

4.1 Experiences with 802.11b Data Rate

To determine the usability of 802.11b WLAN for EMMA we performed some field tests. The main focus was the behavior of 802.11b WLAN cards in scenarios with high mobility. Special attention was turned out how long two vehicles driving past each other with a relative speed of 40–80 km/h are able to exchange data. To measure the signal strength and the WLAN connection speed we equipped two cars with laptops, WLAN cards, external WLAN antennas and GPS receivers. Each of these laptops ran an instance of "gpsping".

Our test site is a mainly flat area with two small buildings right in the direct line of sight between the starting points of our two vehicles. The absolute distance between the starting points is about 370 m. In addition to the two buildings there were also two large trees in the line of sight and an overland line above the area. Figure 6 shows an overview of the chosen area and the way the vehicles drove to accomplish the exercise. According to our research the speed of two public transportation vehicles driving past each other in real life nearly never exceeds a relative speed of 80 km/h with an average speed of about 60 km/h in urban scenarios.

Figure 7(a) shows a measurement with a relative speed of 40 km/h and two vehicles driving past each other. Although the wireless connection drops in speed because of the building in the line of sight there are still 20 s left to transfer data at full 11 Mbit/s. Taking into account that the effective data rate of the WLAN is significantly lower than the nominal rate (approx. 5.5 MBit/s vs. 11 MBit/s), this period should be sufficient for transferring about 288.000 result sets with a size of 50 Bytes. Figure 7(b) shows the same test with an relative speed of 80 km/h. In this case, there is still a stable and fast connection available for transmission of measurement result sets. The connection was available for 10 s at 11 Mbit/s and for another 9 s at 5.5 Mbit/s. Based on the same assumptions as above this leads to about 209.000 result sets being transferred during the shorter period.

The results show that the relative speed of the two vehicles does influence the number of result sets being transferred while the vehicles are driving past each

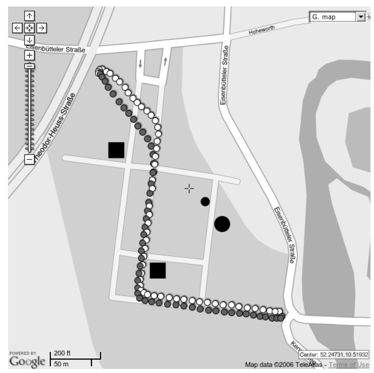
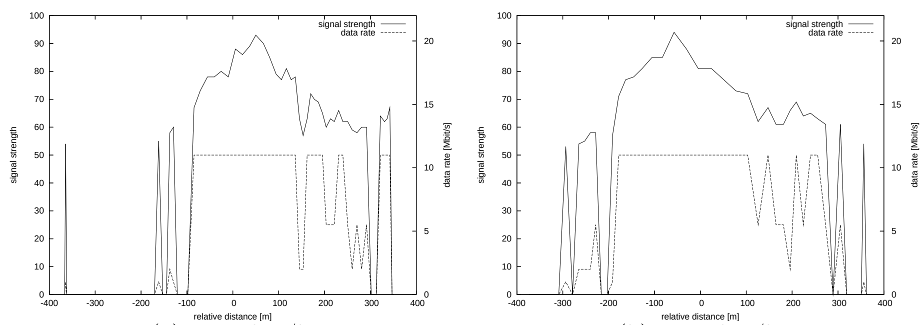


Fig. 6. Measurement environment

other. The main reason for this is not a degraded performance of 802.11b due to the higher speed, but the shorter time that is available for data transmission.



(a) v=40 km/h (b) v=80 km/h

Fig. 7. 802.11 performance at different relative vehicle speeds

4.2 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. This test is 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 an dense residential area in Braunschweig.

The lines in figures 8(a-d) depict the traces of the two cars. The arrows point in the driving direction and the dots mark an available WLAN connection between the two nodes. The WLAN connection status was probed once a second.

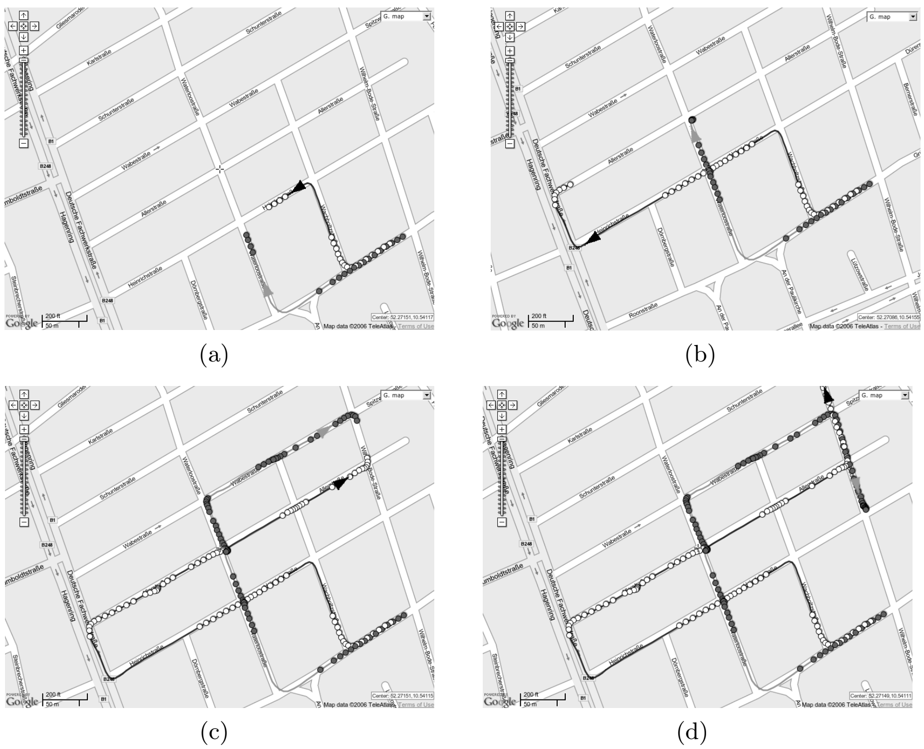


Fig. 8. Scenario for evaluating the 802.11 performance

Thus, each successful probe is represented by a dot on the map, indicating the speed and the time the two nodes had a wireless connection.

At the beginning of the test drive (figure 8(a)), the distance between the two nodes is increasing, since they are driving different ways towards the next intersection. The wireless connection is stable for about eight additional seconds after the line-of-sight between the vehicles was lost. The same effect can be observed when crossing the next intersection. The wireless connection starts working again several seconds before arriving at the intersection.

Figure 8(b) shows that the two nodes had about 16 s to exchange data at the first intersection even without having a line-of-sight. Moreover, it can be seen that even in high-density areas the two vehicles are already within wireless transmission range at a distance of about 300 m.

The time within wireless range at the second intersection was about 30 s (figure 8(c)), which is enough time to exchange a fair amount of result sets. Interestingly it can be observed that there is also a wireless connection when the two vehicles are passing the same crossroad at a similar time. The rare connections even without line-of-sight are explainable by multipath propagation effects as well as vacant lots.

Figure 8(d) shows the range of WLAN on straight streets. As indicated by the dots the wireless connection was available for more than 40 s while the vehicles drove past each other. This is a typical scenario for public transportation vehicles in a city and shows the feasibility of using WLAN for EMMA.

4.3 DTN measurements

Since the functionality of DTN and the availability of WLAN connections does not yet guarantee the feasibility of EMMA, additional tests on the characteristics of the message dissemination were performed. We use three prototype sensor nodes comprising a laptop running our software connected to a GPS receiver, a WLAN card with an external antenna, and a temperature sensor. A fourth laptop simulated the central evaluation server (CES).

One node was stationarily placed outside of the wireless range of the CES. The CES was placed at the border of the test site. Two other sensor nodes were driving along predefined routes to collect measurement data. This scenario proved that bundles from the stationary node were stored and forwarded by one of the moving nodes and finally reached the CES. In addition the moving sensor nodes needed to store their result sets while outside of the wireless range of the CES and then exchange data when reentering the wireless range of the CES. This is a scenario representing the real world with public transportation vehicles meeting each other, exchanging result sets and storing them while not in range of a relay or gateway. The results of this final test confirmed that the whole system works as planned. Result sets from all over the test site have been acquired and forwarded to the CES for later evaluation. Even the result sets of the stationary sensor node have been forwarded to the CES which proves that DTN is working as intended.

Another result of the test is that the maximum delay of bundles originating from mobile nodes is 75 s (the period between performing a measurement and the time of delivery to the CES). The minimum delay is 1 s as the bundles are transmitted immediately when within wireless range. The maximum delay of bundles acquired by the stationary node is 226 s since these bundles need to be relayed by one of the mobile nodes. The minimum delay of bundles by this node is 1 s. This is because one of the mobile nodes is within wireless range of the CES as well as the stationary node and therefore it acts as direct relay and would forward the arriving bundles immediately. However, not only the minimal and maximal delays are of interest. Another important metric is the average delay. In our scenario the delay is only 6.76 s and thus fairly low. The average delay of a result set from the stationary sensor node is 24.86 s.

4.4 Discussion of the Results

The use of off-the-shelf 802.11 WLAN hardware is one of the main ideas of our concept in order to minimize costs. The field tests were set up to determine whether 802.11 WLAN satisfies EMMA's requirements at wireless communication techniques. We not only evaluated the transmission range, but also the available data rate while driving past each other.

The results of our evaluation are very encouraging, since they show very clearly that the data rate of 802.11 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. This offers great opportunities for large-scale deployments of EMMA. Moreover, we have seen that the system even works well in urban environments. Even with all different kinds of interferences data exchange is still feasible. Finally, we evaluated the usability of the reference implementation of DTN for EMMA. The results showed that it worked as expected. Therefore, its use in the scope of EMMA is very suitable because the software is easy to administrate and to use. It does not require any user interaction or maintenance which lowers the costs for the operator the mobile network.

Although we only used temperature sensors to observe the environment in our scenarios, this is only an example of what it may be used for. Any kind of data acquisition device can be attached to the nodes. In real environmental EMMA might be used to monitor ozone or CO_x-emissions.

5 Conclusion and Outlook

Environmental monitoring and traffic management is an important task in times of increasing traffic densities. Several regulations have been enacted to reduce air pollution and thus to protect the environment. All these regulations go along with additional efforts of monitoring several pollutants in the air in order to control the compliance with emission standards. The measurement data has not only to be collected, but also to be documented and provided to the public (e.g.

residents and tourists). Very often the infringement of the regulation results in penalties against the respective local authority and may also be connected with strict bans on driving. Although today most regulations are interpreted very widely, it can be expected that the prescriptive values will be reduced in the future and the compliance with environmental regulations will be enforced.

Currently the measurement of air pollution is realized on the basis of few stationary measurement stations. The concentration of harmful substances in the air is predicted based on the measured data in combination with complex mathematical models. Nevertheless, this predictive approach goes along with inaccuracies and is not very well suited for realizing a sustainable traffic management in order to avoid exceeding prescriptive values and a complete information of the population. Thus, instead of using few fixed measurement stations, a mobile and distributed measurement network can be used to gather area wide measurements of the air pollution. Most larger cities have more or less dense overground public transportation networks using buses and/or trams. These networks connect the outskirts of a city with the city center as well as all major points in the city. For this reason, they are very well suited for our approach. The communication architecture presented in this paper provides the basis for realizing 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 less fixed infrastructure components. Using the DTN approach, measurement data is spread through the network to a central evaluation server that analyzes and combines the incoming data of all parts of a city. A local evaluation of measurement data by the nodes or intelligent display panels along main streets is possible as well. The architecture is based on standard 802.11 WLAN technology which is cost-efficient. Basically, any public WLAN hotspot can be used to forward measured data to the evaluation server. In addition, people who are sensitive to specific pollutants can 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. If desired, the system can be easily extended with an additional Bluetooth interface. EMMA can 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 802.11 WLAN is perfectly usable to communicate between measurement 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. Even the transmission rate if 802.11b is sufficient for the transfer of more than 200.000 results sets per "meeting" of two vehicles. The DTN reference implementation works as advertised and thus is also usable to complete the architecture of EMMA. The field test revealed that the whole system of EMMA works and is usable for more advanced testing like a large-scale field deployment.

However, the purpose of EMMA is not only limited to realizing a distributed measurement system. The Internet gateways may not exclusively be used to connect the mobile network with the evaluation server, but also to offer several other information services as well as Internet access. A passenger information system using the EMMA architecture may e.g. include the distribution of news or special announcements of current events in the city. Other static information services may provide maps about the area around a bus stop to tourists or information about restaurants or bars nearby. At the time Car2X technology is introduced to mass-production vehicles, these vehicles may also benefit from the Information services provided by EMMA.

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