INTEGRATING SMARTDUST INTO INTELLIGENT TRANSPORTATION SYSTEMS

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ABSTRACT. The last few years have seen the emergence of many new technologies that can potentially have major impacts on Intelligent Transportation Systems (ITS). One of these technologies is a micro-electromechanical device called smartdust. A smartdust device (or a mote) is typically composed of a processing unit, some memory, and a radio chip, which allows it to communicate wirelessly with other motes within range. These motes can also be augmented with additional sensors – such as those for detecting light, temperature and acceleration – hence enhancing their features and making their application areas virtually limitless.

As the smartdust concept is still relatively new, and very little is known about its application in transport domain, conducting research in this area may prove to be very valuable. It is generally perceived that smartdust will become the low-cost, ubiquitous sensor of the future, especially once its size shrinks dramatically to merit its name.

Our involvement in several transport-related EU and UK funded projects (ASTRA, 2005; ASK-IT, 2007; EMMA, 2007; Foot-LITE, 2007; MESSAGE, 2007; TRACKSS, 2007) provides us with an opportunity to carry out experiments and to develop demonstrations of smartdust applications in transport systems. We also have a chance to investigate how smartdust can be used in collaboration with other (more traditional) transport sensors for developing better Co-operative Transport Systems (CTS).

This paper outlines our experience in these projects and provides an illustration on the important role that the smartdust technology can play in future ITS. We also present encouraging results obtained from our experiments in investigating the feasibility of utilising smartdust in real ITS applications.

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INTRODUCTION

A recent study by the UK Governments Office of Science and Innovation, which examined how future intelligent infrastructure would evolve to support transportation over the next 50 years looked at a range of new technologies, systems and services that may emerge over that period (Blythe, 2006; Foresight, 2006). One key class of technology that was identified as having a significant role in delivering future intelligence to the transport sector were wireless sensor networks and in particular the fusion of fixed and mobile networks to help deliver a safe, sustainable and robust future transport system based on the better collection of data, its processing and dissemination and the intelligent use of the data in a fully connected environment (Tully, 2006). As future intelligent infrastructure will bring together and connect individuals, vehicles and infrastructure through wireless communications, it is critical that robust communications protocols are developed. Moreover, road networks currently are not widely fitted with wireless infrastructure, although the recent M3 trials by the Highways Agency and the 'intelligent corridor' trials in Newcastle (UK) both trialled such infrastructure (Sharif *et al.*, 2007).

Mobile Ad-hoc Networks (MANETs) are self-organising mobile networks where nodes exchange data without the need for an underlying infrastructure. In the road transport domain, schemes which are fully infrastructure-less and those which use a combination of fixed (infrastructure) devices and mobile devices fitted to vehicles and other moving objects are of significant interest to the ITS community as they have the potential to deliver a 'connected environment' where individuals, vehicles and infrastructure can co-exist and cooperate, thus delivering more knowledge about the transport environment, the state of the network and who indeed is travelling or wishes to travel. This may offer benefits in terms of real-time management, optimisation of transport systems, intelligent design and the use of such systems for innovative road charging and possibly carbon trading schemes as well as through the CVHS (Cooperative Vehicle and Highway Systems) for safety and control applications. Within the vehicle, the devices may provide wireless connection to various Information and Communications Technologies (ICT) components in the vehicle and connect with sensors and other nodes within the engine management system.

Newcastle University has been at the forefront of research into the technology challenges of using these small, low-cost and smart wireless sensors in Transport and the application areas where they could be employed. It is clear to the ITS community that the emergence of low cost sensors will open up new paradigms in how we can pervasively collect data from sensors, convey information along fixed and mobile low cost wireless networks (partly or fully formed or ad-hoc) and provide pervasive connectivity between people, vehicles and infrastructure. A number of the key projects undertaken in this area are briefly described below:

- **Applications of Smartdust in Transport (ASTRA)**

  The ASTRA project (ASTRA, 2005) investigated the use of mobile ad-hoc networks, and more specifically, smartdust for transport applications. The project examined the current state-of-the-art with smartdust, using MICA2 motes (Crossbow, 2007) as the technology to be tested. It also looked at the likely market and technological advances of the smartdust technology over the coming decade.

  A trial using smartdust technology was hosted in Newcastle with a pervasive intelligent corridor established by a network of fixed motes on roads near Newcastle Central Station.

Mobile motes were also placed in several buses. Communication between a static mote and a moving mote on-board a vehicle was achieved, showing that communication can take place between road side and vehicles using a network of motes (Blythe *et al.*, 2005).

- **Technologies for Road Advanced Cooperative Knowledge Sharing Sensors (TRACKSS)**

The focus of the EU funded TRACKSS project (TRACKSS, 2007) is to research advanced communications concepts, open interoperable and scalable system architectures that allow easy upgrading, advanced sensor infrastructure, dependable software, robust positioning technologies and their integration into intelligent co-operative systems to support a range of core functions in the areas of road and vehicle safety and traffic management and control. The overall aim is to develop new systems for cooperative sensing and predict flows, infrastructure and environmental conditions surrounding traffic, with a view to improving road transport safety and efficiency. To support the demonstration phase of the project, Newcastle University will develop a new technology for 'smart' detection on vehicles and infrastructure and a common framework for data collection and access from the entire array of sensors being deployed and tested in the TRACKSS project.

- **Embedded Middleware in Mobility Applications (EMMA)**

The EMMA project (EMMA, 2007) is funded by the EU and has an overarching goal of utilising new embedded middleware to support the underlying logic and communications required for future cooperating wireless objects and the applications they may support in the automotive and road transport domains. This trend in the deployment of digital processing widely into the environment – what is variously called ambient intelligence, ubiquitous computing, the internet of things, or just 'smart' technology – goes well beyond transport and will impact on almost every aspect of our lives. Just as the World Wide Web was a one-time transition in the technology landscape, bringing information into a globally integrated system, so we are just at the start of another one-time transition, linking up things through embedded intelligence and communications.

In the case of EMMA, the things being automobiles and their constituent parts, and the infrastructure they utilise (both physical in the sense of roads and the ICT embedded in them for monitoring and control purposes). If we think more widely at present, most of the world's computing power is already embedded invisibly into the things around us. The personal computers, music players and other gadgets are just the tip of the iceberg. They probably represent no more than 1% of the computing power we have deployed around us. A typical car today will have at least 20 microprocessors and a host of other electronics contributing to the general functionality required by a modern car as well as the 'value added services' which may be the USP (Unique Selling Point) of a particular vehicle – whether the application, be: better information on how the vehicle is running; safety applications; or infotainment in the vehicle to name but three.

The EMMA project is committed to deliver a middleware platform and a development environment which facilitates the design and implementation of embedded software for cooperative sensing objects. The ultimate aim that the project will focus on delivering, is to hide the complexity of the underlying infrastructure whilst providing open interfaces to 3rd parties enabling the faster, cost-efficient development of new cooperative sensing

applications. This end-product will be accompanied by a publicly available specification (PAS) that will help to facilitate its wider adoption.

- **Ambient intelligence System of agents for Knowledge-based and integrated services for mobility impaired users (ASK-IT)**

ASK-IT (ASK-IT, 2007) uses ambient intelligence technology to provide functions and services for older and disabled people in various environments, including home, work, leisure and transport. The main features include: mediation of content and services; seamless environment management (anywhere, anytime); user preference and context-related processes; flexible geo-referenced services; and a user confidence based environment. The first phase of the research involves the collection of info-mobility content relating to the environments described above. In the leisure and tourism sector, for example, this might include details of accessibility to cinemas, sports venues or restaurants. This content is then integrated with different tools, including enhanced accuracy localisation, accessible inter-modal route guidance modules, and interfaces to e-commerce/e-payment, e-working, e-learning systems and assistive devices. It is envisaged that this framework will be interoperable in terms of mobile devices and local and wide area networks. The integrated ASK-IT services and system will be tested in a number of interconnected cities/areas across Europe, to prove that accessibility for disabled users can be achieved in a reliable, seamless and viable way, using a range of available technologies and communication networks. Newcastle is developing a wireless network for outdoor navigation and localisation system that can inform and assist mobility impaired travellers in a range or urban environments when travelling and visiting points of interest (Edwards and Blythe, 2004).

- **Mobile Environmental Sensing System Across Grid Environments (MESSAGE)**

The MESSAGE research project (MESSAGE, 2007) is an important new initiative involving five universities, and funded jointly by UK Engineering and Physical Sciences Research Council (EPSRC) and the Department for Transport (DfT). The project involves developing new techniques for collecting, managing and interpreting data on environmental quality and its relationship to transport. The overall aim of the project is to address key scientific challenges in the field of transport and environmental monitoring, using data derived from transportable sensors which can measure local environmental factors such as pollutants from vehicles.

Utilising the expertise and track record of the ITS research team, Newcastle University is developing and testing a wireless ad-hoc sensor network using smartdust to pervasively sense traffic pollution on the road network of Gateshead (UK). This is a unique opportunity to pervasively sense pollution generated from road traffic, through the deployment of up to 300 wireless sensors in the street-side infrastructure of Gateshead to measure pollutants and detect vehicle flows. The real-time monitoring of the environment pollution will be used to explore how traffic control and real-time demand management measures could be implemented to mitigate the pollution episodes. Once the science and technology research challenges are resolved at the Gateshead test site, a second set of wireless sensors will be deployed and integrated with the instrumented city facility in Leicester (UK) and tested with real traffic control strategies (Blythe *et al.*, 2006).

The MESSAGE project team in Newcastle builds on previous multi-disciplinary collaborations across the University and bring together the ITS and environmental team of the Transport Operations Research Group, with the wireless sensor group of the School of Electrical Engineering and the e-Science researchers of the North East e-Science Centre.

- **Foot-LITE**

  The Foot-LITE project (Foot-LITE, 2007) is funded by the UK EPSRC, DfT and Department of Trade and Industry (DTI). The project will deliver innovative driver/vehicle interface systems and services to encourage sustained changes to driving styles and behaviours which are safer, reduce congestion, enhance sustainability, help reduce traffic pollution emissions, and reduce other social and environmental impacts. Fundamental research will be used to support the strong industry base in the project through prototype systems development and design, impact assessments and the further development of research tools and processes to deliver a credible evidence-based validation of the system through to real-world operational experiences with user feedback and evaluation.

  The Foot-LITE system is seen as a tool to encourage and challenge drivers to achieve very real benefits that are already available in the current vehicle fleet but whose benefits cannot be readily maximised without an advisory interface to the driver. The approach has the ultimate choice and control still resting with the individual. This is seen to be crucial to the public and commercial acceptability of Foot-LITE. The aim of the Foot-LITE project is to create a revolutionary driver information system designed to educate and encourage safer and greener driving and longer term behavioural changes. The vehicles will be in communication with a wireless network established at the roadside for environmental monitoring and control functions.

These projects are beginning to deliver research evidence that the wireless ad-hoc networks can be used within the transport environment, for automotive applications (EMMA, TRACKSS and Foot-LITE), road to vehicle communications (ASTRA, EMMA, TRACKSS and Foot-LITE), sensor applications (TRACKSS and MESSAGE) and for personal communications and localisation (ASK-IT and MESSAGE). There are still key challenges with respect to robust protocols, miniaturisation, battery, antennae and sensor design, however the applications tested and evaluated are beginning to show that we are not too far away from having the ability to deploy these wireless low-cost sensor networks pervasively to enhance the management and control of transport networks and deliver new connectivity between people, infrastructure and vehicles.

This paper will focus on the research and subsequent trials of the wireless technology within the two EU funded project, EMMA and TRACKSS.

CHALLENGES IN THE EMMA AND TRACKSS PROJECTS

The EMMA and TRACKSS projects are committed to play a major role in creating new possibilities in the future ITS by using smartdust technology. The future ITS applications will use not only smartdust technology but also other or existing sensor technologies such as inductive loop sensor, radar sensor and artificial vision sensor. Integrating smartdust with other sensors is one of the big challenges and this can be achieved by creating middleware technologies for ITS applications. Furthermore, middleware masks the heterogeneity of

sensors, operating systems, and communication technologies to facilitate application programming and management (Geihs, 2001).

Figure 1: EMMA project hierarchical approach

Smartdust devices are in the early stages of dominating wireless sensor network applications. Initial studies suggest vehicle to vehicle, vehicle to infrastructure and infrastructure to infrastructure communication and in-vehicle monitoring and environmental monitoring may exist for smartdust in the transport domain. Over the last few years, many different versions of smartdust devices have been designed and built by various companies and institutions. Such devices can be used to sense a wide range of environmental parameters as well as vehicle speed, vehicle direction and vehicle presence in the infrastructure. Smartdust can also be used as a bridge to form a network with other sensors. Even though there are several platforms available on the market, Crossbow MICA family motes (Crossbow, 2007) will be used in EMMA and TRACKSS projects due to its commercial success in many wireless sensor network applications. Also, Newcastle University has successfully used MICA family motes in its other research projects (such as the ASTRA project described earlier). Low power wireless communication and low power sensing capabilities are essential for sensor network applications which are supported by these MICA family motes.

Another challenge is choosing appropriate communication technology for ITS applications. Moving vehicles need be able to exchange data with static infrastructure or with other vehicles. The projects have to discover which communication technologies can be used and how the networks are formed by sensors from different levels. Zigbee protocol is a new standard for low cost wireless sensor networks but it is still under development (Zigbee Alliance, 2007). Zigbee uses the media access control layer and physical layer of IEEE 802.15.4 for communications between devices. It offers a short range wireless networking capability with low cost, low bit rate and low power consumption. The projects use Zigbee as a wireless communication protocol to form a network between smartdust devices and other sensors – we use the MICAz version of the motes, which is equipped with Zigbee radio chip (Selvarajah and Tully, 2007). Since Zigbee is mainly designed for fixed networks, *mobility issues* in the Zigbee protocol will be investigated.

The EMMA project will investigate an energy efficient and distributed way of data forwarding/gathering between the sensors at the infrastructure and sensors at the car level. The projects will also address the problem of resource allocation such as how to allocate limited energy, radio bandwidth and other resources to maximise the value of sensors contribution to the network. The projects have to address the issue of wireless networking concepts at the engine level and at the vehicle level (see Figure 1). At the engine level, wireless communication would enable a much wider freedom in the engine design, resolve some problems in the production chain and reduce wired connections and hence cost. Again, safety-critical and wireless communications are sometimes considered as contradicting terms,

as a result the middleware will have to handle the issues of using wireless communication for safety- critical system in the transport domain.

Due to the limited resources of smartdust (e.g., memory, power), the middleware itself should be lightweight in terms of communication and computational requirements. In practice, there may be different versions of middleware according to the capabilities of the platform – lightweight versus heavyweight. As wireless sensor networks range from small applications to big applications with thousands of nodes in the future ITS applications, the middleware technologies need to resolve these scalability issues while maintaining acceptable performance levels of the real time services with heterogeneous sensor network devices.

Middleware needs adapters for each operating system (OS) to convert the middleware independent functions to the appropriate OS functions (e.g.,TinyOS, NanoQplus, PowerPC). The adapters also include conversions for the Application Program Interface (API) of different communication technologies, e.g. Zigbee or CAN (Controller Area Network) (Cena *et al.*, 2005). The EMMA project may need to use different communication technologies at different levels for specific applications. For example CAN or Flexray (Cena *et al.*, 2005) can be used for in-vehicle communication while Zigbee can be used for vehicle to infrastructure communication. Each communication technology uses, for example, a different addressing scheme that has to be hidden from the EMMA applications through the EMMA middleware.
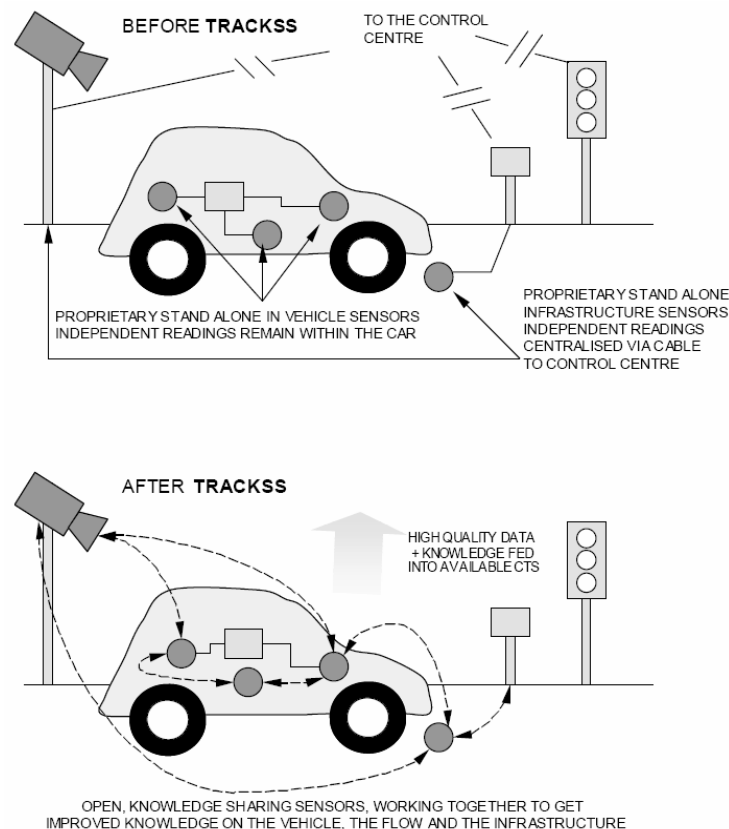

Figure 2: TRACKSS concept

For the TRACKSS project, the focus is on achieving improved collaborations among the diverse sensors deployed both on infrastructure and on vehicle. This is achieved by augmenting each sensor with *knowledge sharing* capabilities, allowing them to share their

data with other sensors, and/or with the traffic authorities (see Figure 2). These Knowledge Sharing Sensors (KSS) are therefore optimally integrated into the Cooperative Transport Systems (CTS) environment using the Knowledge Sharing Model (KSM) designed and developed by the TRACKSS consortium.

Among others, Newcastle University's contribution is through the development of smartdust software that incorporates the TRACKSS KSM, turning the MICAz motes into smartdust KSS. We are involved in several collaboration scenarios with other sensors, such as one with the advance vehicle identification camera from Laboratoire Central des Ponts et Chaussées (LCPC – French Public Works Research Laboratory), for accurate detection and identification of road signs.

Since there is still limited information on how Zigbee (in general) and smartdust through MICA family motes (in particular) perform in transport applications – where communication will involve motes travelling at high speed – we devised and carried out several experiments to find out. These experiments are described in the section below.

EXPERIMENTS

We had conducted two sets of experiments in order to explore the feasibility of using smartdust in transport domain. The "earlier experiments" provided the foundation of our exploration by thoroughly investigating the many factors involved in deploying smartdust motes in moving vehicles. The "later experiments" built on the earlier experiments by focussing on the effect of vehicle travelling at higher speed on the smartdust communication.

Earlier Experiments

This earlier set of experiments was performed as part of an MSc dissertation (Fairchild, 2004).

Purpose

Initial experiments were performed in two phases; the first set of experiments determined some simple features of the motes in an open space:

- The most efficient planar orientation in open space
- The signal degradation over distance in open space
- The standard data transmission error rate of the motes

The second set of experiments was designed to characterise the behaviour of the motes in a transport application:

- The effect of orientation and placement of the motes when positioned inside a vehicle
- The effect of height and position of the mote within the road infrastructure
- The effect of speed of the vehicle passing an infrastructure mote

Setup

The experiment list is as follows:

Phase 1:
      1.1 Signal degradation over distance
      1.2 Effect of antenna orientation
      1.3 Standard error rate

Phase 2:
      2.1 Mote at high level at three speeds
      2.2 Mote at low level at five speeds
      2.3 Mote at three low level heights
      2.4 Mote at low level, at three distances from kerb
      2.5 Mote position within vehicle

In these experiments, two motes were used. One mote was a 'logger' mote and one an 'echo' mote. The logger mote transmits a number which is received and re-transmitted by the echo mote. The logger mote receives this and logs the number and the received signal strength indicator (RSSI) – a value relative to the strength of the received signal. The RSSI value was then converted into a received voltage and received absolute power level for comparison. Some experimental setups required the motes to be placed in neutral orientation. This means arranging the motes so that the aerial end of the mote body is closest and in line with the antenna end of the second mote.
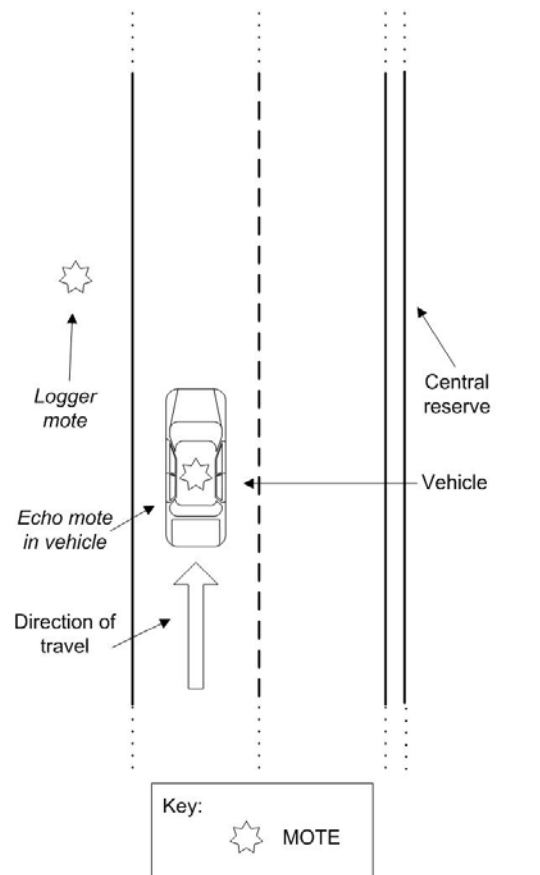

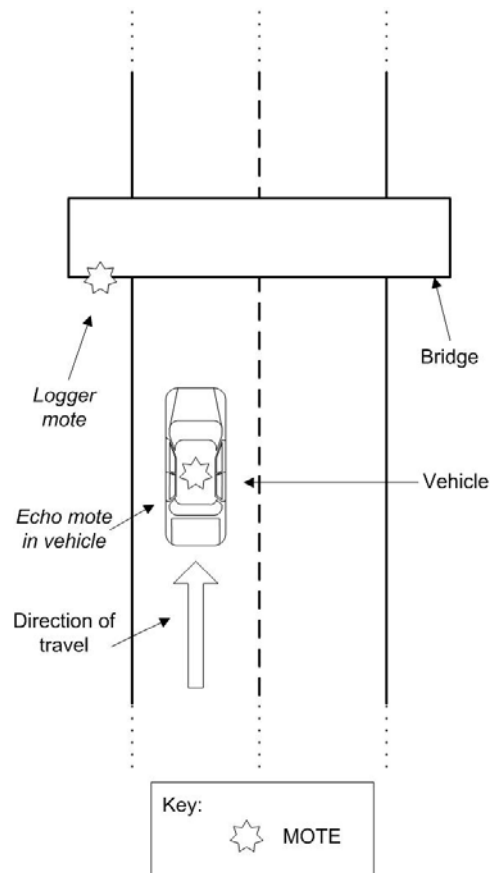Figure 3: Experimental setup at low level

Figure 4: Experimental setup at high level

Experiment 1.1 - Signal degradation over distance

1. The logger and echo mote are placed 100m away from each other in an open outdoor space. The motes are both 20cm from the ground.
2. The logger mote is switched on and the echo mote is moved towards the logger mote at a constant speed of $1.3ms^{-1}$ until the echo mote reaches the logger mote and the logger mote is switched off.

Experiment 1.2 - Effect of antenna orientation

1. The logger and echo mote are placed 20m away from each other at a height of 20cm from the ground in an open outdoor space.
2. The echo mote is setup so that it is in line with the logger more and in neutral orientation. That is that the antenna end of the logger mote and the antenna end of the echo mote are facing each other.
3. The echo mote is switched on for ten seconds and then switched off again.
4. The orientation of the echo mote is changed according to the diagram below, and step three is repeated.
5. Step four is repeated until the echo mote has been recorded in all eight orientations (Figure 5).
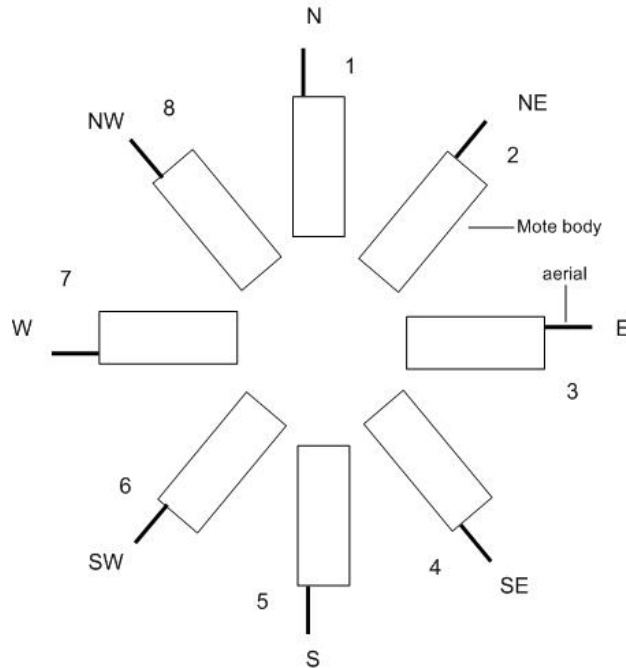
Figure 5: Eight orientations of the mote

Experiment 1.3 - Standard error rate

1. Echo and logger mote are placed on platform at 100cm high, 500cm apart, with no obstacles in the way in neutral orientation
2. Echo and logger mote switched on
3. At one hour intervals data will be collected and the motes will be reset. This is repeated until five hours worth of data has been collected.

Experiment 2.1 - Mote at high level at three speeds

1. The logger mote is placed on a bridge over a road, 795cm from the ground, directly over the centre of the carriageway. The echo mote is placed on the middle of the dashboard of a vehicle 80cm from the ground.
2. The vehicle performs loops of the road, passing under the bridge.
3. The echo mote passes under the bridge 5 times at 20, 30 and 40 miles per hour (mph).

Experiment 2.2 - Mote at low level at five speeds

1. The logger mote is placed on a stand 100 cm from the ground, 200cm away from the kerb. The echo mote is placed on the middle of the dashboard of a vehicle 80cm from the ground.
2. The vehicle performs loops of the road, passing by the stand.
3. The echo mote passes by the stand 5 times at 10, 20, 30, 40 and 50 mph.

Experiment 2.3 - Mote at three low level heights

1. The logger mote is placed on a stand of variable height, 200cm away from the kerb. The echo mote is placed on the middle of the dashboard of a vehicle 80cm from the ground.

2. The vehicle performs loops of the road at a constant speed of 40 mph, passing by the stand.
3. The mote passes by the stand 5 times with the stand set to 80, 100 and 150 cm.

Experiment 2.4 - Mote at low level, at three distances from kerb

1. The logger mote is placed on a stand 80cm from the ground at a variable distance from the kerb. The echo mote is placed on the middle of the dashboard of a vehicle 80cm from the ground.
2. The vehicle performs loops of the road at a constant speed of 40 mph, passing by the stand.
3. The mote passes by the stand 5 times with the stand at 0, 100 and 200 cm from the kerb.

Experiment 2.5 - Mote position within vehicle

1. The logger mote is placed on a stand 80cm from the ground, 80cm from the kerb. The echo mote is placed on the middle of the dashboard of a vehicle 80cm from the ground.
2. The vehicle performs loops of the road at a constant speed of 40 mph, passing by the stand.
3. The mote passes by the stand 5 times in four different positions in the car; on the dashboard (Figure 6), in the window horizontally, in the window vertically and in the glove box.

Figure 6: Mote placement on the dashboard

Results
The first phase of experiments showed that the average distance of good transmission was around 20m, and varied almost linearly from closest position. The orientation that allowed the receiving of the strongest signal was when the motes were lined up one in front of the other, both facing the same direction. The average standard error rate was 3.20% with a standard deviation of 0.038.
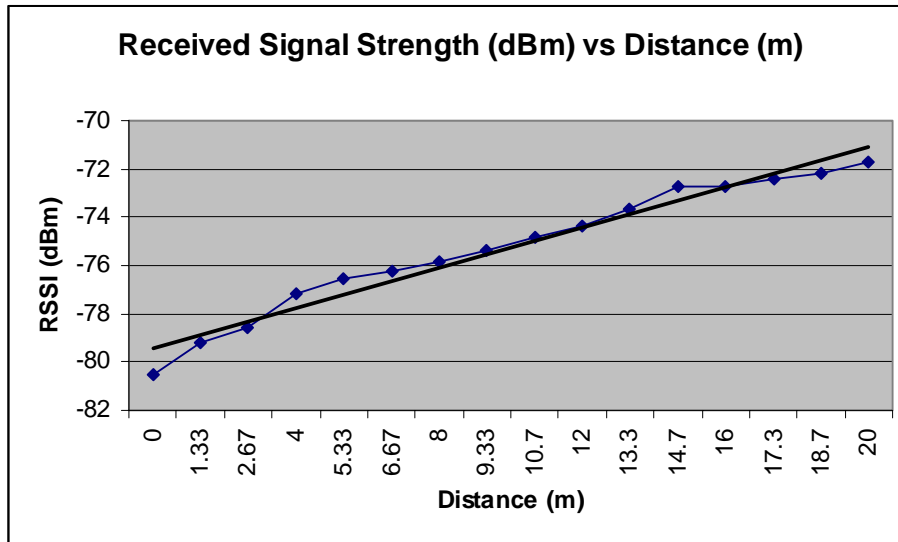
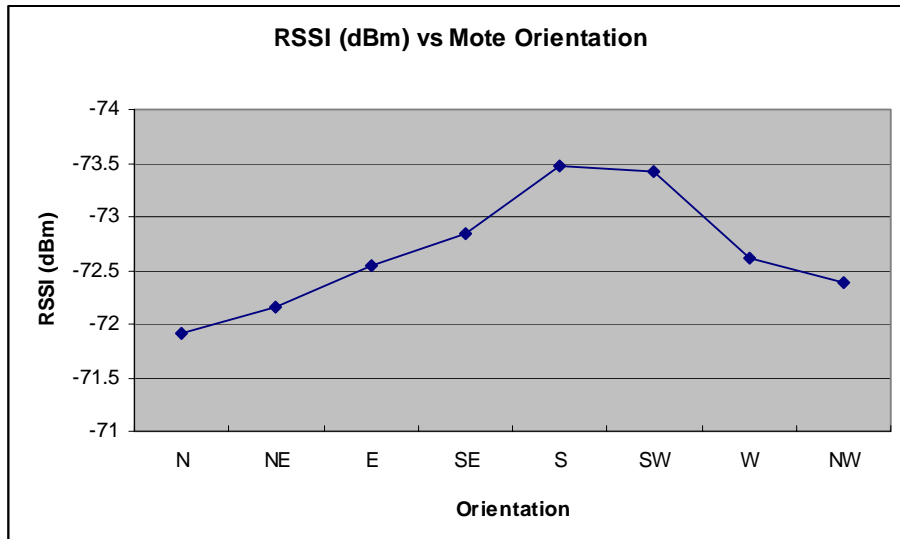Figure 7: Experiment 1.1, Signal degradation over distance

Figure 8: Experiment 1.2, Effect of antenna orientation

The data collected from the second phase of results gave six sets of figures.

Transaction length: the number of frames received
Average transaction time: the average transaction time is the number of frames received at the constant data rate of 2Hz.
Error rate: the percentage of frames dropped (erroneous) within the transaction time.
Actual transaction time: the actual number of useful frames received at the constant data rate of 2Hz.
Average (non 0) RSSI: the average of the received frames RSSI value, not counting those that were recorded as 0 (dropped).

Experiment 2.1 showed a reduction in average transaction length and average actual transaction time. However, the average error rate was a fairly constant as was the average RSSI. For the 30mph run, the average error rate is lower than that recorded for 20mph or 40mph (see Table 1).

Table 1: Results from experiment 2.1 - Mote at high level at three speeds

Speed	Average transaction time	Average transaction length	Average dropped frames	Average error rate	Average Actual time	Average non 0 received power
(mph)	(s)	(frames)	(frames)	(%)	(s)	(RSSI)
20	10.1	20.2	5.5	27.3	7.3	180.13
30	9.2	18.4	4.4	23.9	7.0	178.6
40	6.9	13.8	3.8	27.5	5.0	184.4

Experiment 2.2 showed that for the same speeds as 2.1, the average transaction time was almost half that as recorded in 2.1 and further decreased with speed. The error rate dropped significantly with speed and the average power increased with speed (see Table 2).

Table 2: Results from experiment 2.2 - Mote at low level at five speeds

Speed	Average transaction time	Average transaction length	Average dropped frames	Average error rate	Average Actual time	Average non 0 received power
(mph)	(s)	(frames)	(frames)	(%)	(s)	(RSSI)
10	11.6	23.2	6.2	26.7	8.5	187.06
20	5.7	11.4	2.4	21.1	4.5	187.46
30	2.4	4.8	0.8	16.7	2.0	191.82
40	3.3	6.6	0.8	12.1	2.9	192.13
50	2.6	5.2	0.6	11.5	2.3	192.34

Experiment 2.3 showed as the mote height was increased, the transaction time increased with a lower error rate, but with no real change in average received power (see Table 3).

Table 3: Results from experiment 2.3 - Mote at three low level heights

Mote height	Average transaction time	Average transaction length	Average dropped frames	Average error rate	Average Actual time	Average non 0 received power
(cm)	(s)	(frames)	(frames)	(%)	(s)	(RSSI)
80	3.3	6.6	0.8	12.1	2.9	192.1
100	4.6	9.2	0.6	6.5	4.3	194.1
150	6.0	12.0	1.0	8.3	5.5	191.9

Experiment 2.4 showed that as the mote was moved away from the kerb, the transaction time decreased and gave more errors, with no real change in received power (see Table 4).

Table 4: Results from experiment 2.4 - Mote at low level, at three distances from kerb

Distance from kerb	Average transaction time	Average transaction length	Average dropped frames	Average error rate	Average Actual time	Average non 0 received power
(cm)	(s)	(frames)	(frames)	(%)	(s)	(RSSI)
0	4.7	9.4	0.8	8.5	4.3	194.85
100	4.2	8.4	1.0	11.9	3.7	197.18
200	3.3	6.6	0.8	12.1	2.9	192.13

Experiment 2.5 showed that having the echo mote in the side window closest to the logger mote gave some advantage in transaction length, however this was marginal. Received power

did not change significantly and the error rate was inconsistent across the set of results (see Table 5).

Table 5: Results from experiment 2.5 - Mote position within vehicle

Orientation	Average transaction time	Average transaction length	Average dropped frames	Average error rate	Average Actual time	Average non 0 received power
(position)	(s)	(frames)	(frames)	(%)	(s)	(RSSI)
Dashboard	3.3	6.6	0.8	12.1	2.9	192.13
Side window: horizontally	5.7	11.4	2.0	17.5	4.7	197.15
Side window: vertically	4.6	9.2	0.0	0.0	4.6	194.02
Glove box	2.7	5.4	0.4	7.4	2.5	197.44

Later Experiments

Purpose

The earlier experiments have demonstrated that motes can be used for communication between a fixed infrastructure and a moving vehicle up to a speed of 50 mph. It was decided to further test the devices at higher speeds (60 and 70 mph) to asses the suitability of smartdust in applications alongside fast moving roads such as a motorway.

Setup

The experimental setup was similar to the earlier series of experiments:

- Two motes were used.
- *Mote A* was placed on the dashboard of a car, connected to a laptop (which was used to store the results).
- *Mote B* was suspended on a motorway bridge, approximately 6 meters over the centre of the motorway carriageway the vehicle would pass under.
- *Mote A* broadcasts a packet every 250 milliseconds. Upon receiving this packet, *Mote B* echoes it back to *Mote A*.
- *Mote A* records the number of packets communicated between the two motes (i.e. A → B → A).
- The experiment was conducted on a section of the A1 motorway near Newcastle upon Tyne (UK) in bright clear conditions.
- The vehicle was travelling at the speed of 60mph (approximately 96 km/h) or 70mph (approximately 112 km/h) when passing under *Mote B* on the motorway bridge.

Results

Several passes were made and the results can be seen on Table 6. On average, 7.75 packets were successfully communicated when the vehicle was travelling at 60 mph, and 6.17 packets at 70 mph. Since the packets were broadcast every 0.25 seconds, it can be calculated that the communication windows are 1.94 seconds and 1.54 seconds respectively.

<div align="center">Table 6: Results from later series of experiments</div>

Pass	Speed			
	60mph		70mph	
	No. of packets	Transaction time (s)	No. of packets	Transaction time (s)
1	4	1	5	1.25
2	10	2.5	6	1.5
3	8	2	7	1.75
4	9	2.25	12	3
5			4	1
6			3	0.75
Average	7.75	1.94	6.17	1.54

Discussion

Earlier series of experiments

The communication error rate increases with movement, from 3.20% when in a stationary position to a series wide average of 14.62%. In experiment 2.1, the error rate for 30mph is lower than that for 20mph and 40mph, this could be an error, but the experiment was run five times. It is more likely that the error occurs because the number of received frames is low, a drop rate of 1 frame in 20 is 5%, hence when viewing the error rate, it is worth considering a range of ±5%.

As the speed increases, the transaction time decreases as the motes are in range for a shorter period of time. This means that the received power is higher as it is only when the motes are in range that the packets received.

Because the error rate is a function of number of dropped frames and received frames it appears that the error increases with speed. But because the number of received frames is reducing, a constant number of errors might conceivably give the same results. The number of dropped frames occurs at an average of 1.82.

The height from the ground of the mote is important, higher is better than lower for received packets, probably due to ground absorption, reflection and scattering. Positioning horizontally is also important, closer to the kerb is best. It is suggested therefore that the best methods of locating motes within the road infrastructure are high up and as close to the kerb as possible such as at the end of a street lamp which would also provide power. However on multi-lane roads such as motorways, motes over the middle of the road would be more suitable, or one mote per lane which would infer mounting on gantries, preferably existing ones with power available.

Encasing the mote in the glove box shows the lowest transaction time, having the mote horizontally in the window proves to be the best position which provides the longest transaction time followed by placing the mote in the window horizontally. Although the experiments show a 0% error rate for the horizontal placement, it was probably just a quirk of that series of runs.

To this end, it is suggested that the mote be positioned in the vehicle as close to a glass surface as possible. When mounting the infrastructure mote on a gantry over the middle of the

lane, this lends itself to placing the vehicle mote in the windscreen, mounted behind the rear view mirror out of sight.

<u>Later series of experiments</u>

The later series of experiments were essentially an extension of experiment 2.1 showing the full range of speeds that the motes can be used. These later experiments demonstrated that smartdust can be used for communication between a fixed infrastructure mote and also a fast moving vehicle-based mote. This is an important finding which proves that the Zigbee motes do not suffer from any Doppler effects at normal motorway speeds.

Based on the information gathered from these experiments, it can be calculated that the effective communication range of motes when used with a fast-moving vehicle to be around 50 meters ($\pm$ 5 meters). It is also noted that there is no significant signal degradation when the vehicle travels at a higher speed.

CONTRIBUTION TO THE ITS FIELD

This paper has summarised the research currently undertaken at Newcastle University to investigate the use of wireless sensor networks for road to vehicle communications applications. Considering the wide range of potential uses of these sensors in the transport domain, this is probably the most challenging environment for mobile ad-hoc networks. However, the incorporation of part infrastructure, part mobile based network with fixed points (possibly wireless devices fitted to street-side infrastructure) will broaden the capabilities of such future wireless systems (where investment in the intelligent infrastructure seems appropriate). The business model in the ITS community to invest in such a technology may come when these devices become smaller and cheaper as they are predicted to do over the next 5 years and indeed eventually become pervasive in nature as is envisaged by the 'smartdust concept'.

The projects have already shown that motes are a flexible new technology that can offer dynamic solutions to meet complex traffic scenarios and innovative demand management strategies. Prototypes have been evaluated using frequency bands around the 800-900MHz, 2.45GHz and 5.8-5.9GHz using communication protocols including IEEE 802.11x (WiFi) and IEEE 802.15.4 (Zigbee).

The pervasive nature of the technology enables vehicles to be 'always connected' to the infrastructure in the same way that home broadband users enjoy 'always-on' Internet access thus opening up the scope for an intelligent, configurable ITS infrastructure that will be available for a range of services to support travel and travellers. Thus road users will perceive direct benefits from the introduction of the technology thereby easing user acceptance. The costs of building and maintaining the infrastructure could be amortised over many such services delivered by third-party providers.

Research to deliver this concept of connected mobile devices and infrastructure leads to the opportunity to consider realistically for the first time a fully connected Intelligent Transport System for the future. Recently, the Office of Science and Technology published the findings of the Foresight Intelligent Infrastructure Study (IIS) (Foresight, 2006) which investigated how technology may evolve over the next 50 years to deliver a robust, sustainable and safe transport infrastructure in the future. Among the many recommendations and predictions on

how the technology may deliver more intelligence into infrastructural systems was the view that pervasive wireless systems will have a significant future role in transport.

Concurrently, the use of radio frequency identification (RFID) for transport applications has begun to emerge as a key technology, particularly for use in the freight and logistics sector for tracking containers, pallets, individual products, for car-parking, ticketing and possibly for future road user charging. However Foresight recognised that RFID is just the starting point for a raft of more exciting possibilities with future wireless mobile ad-hoc networks and smartdust, with much more capability and 'intelligence' than current RFID and thus moving towards a more 'all-seeing, all-knowing' environment.

Research is currently focused on filling in the knowledge and technology gaps in pervasive, mobile ad-hoc wireless systems for a range of transport applications. Mobile wireless systems are beginning to be proven as a future tool that will enable the joining up of vehicles, individuals and infrastructure into a single 'connected' intelligent infrastructure system. Embedding this technology in infrastructure – such as environmental sensors in lampposts, embedded in vehicles and infrastructure, in goods, and even connecting individuals through their PDAs, mobile phones, or even bespoke wearable wireless interfaces (PANs – Personal Area Networks) – offer potential for a more all-seeing, all knowing ITS infrastructure. If for example, vehicles are continually in wireless communication with the infrastructure, new paradigms for traffic monitoring and control could be considered, road space allocated more efficiently and incidents dealt with in an optimum way. If vulnerable users have such wireless devices, the infrastructure could warn vehicles to slow down and the drivers to be more vigilant – indeed wireless devices attached to children could for example warn drivers that children are playing out on the street, just around the corner and to reduce speed now. Such devices could help with security and safety of individuals, be used on airline boarding cards and other tickets, and even be used to verify HOV (high occupancy vehicles) or blue badge entitlement. When such a system is also connected to say, a vehicle's CAN-bus, then information on driving style, strange driving behaviour (say where there is a badly maintained stretch of road or object in the road, could be detected from the CAN data – allowing mitigating and maintenance actions to be automatically triggered).

Many of these devices can carry payloads such as sensors, and the idea of monitoring pollution with these devices in a pervasive way is beginning to be researched in the MESSAGE project (with pervasive wireless environmental sensors being attached to lampposts). However if these devices become small and cheap enough (as is the future vision for smartdust) then one could image that we each carry our personal exposure meter. Moreover with 'extreme' sensor design, wireless pollution sensors could be fitted in engine manifolds and exhaust pipes to allow the actual pollution generated by a vehicle to be measured and maybe adjustments to driving style or engine management systems can be advised or made to mitigate some of the pollution effects (early prototypes are being developed at the university at the moment). If future 'carbon allowances' are to be considered in the connected car, the pollution the car generates will also need to be measured and monitored – as proposed in the Smart Market Protocols project where auction and trading-based carbon allowances have been considered.

Wireless PANs on individuals through PDAs, mobile phones, or dedicated devices (such as motes integrated into jewellery – a research project currently in its early stages at Newcastle University) enable individuals to be connected and interact with the infrastructure. This thrust of research will finally provide the missing link in delivering the vision of future pervasive

information delivery, whereby context specific and bespoke traveller information can be delivered to the individual on the move, through embedded screens in infrastructure, on mobile devices and for example on 'terminator' glasses where one is able to display traveller information on the lens of specially adapted spectacles (seen as particularly beneficial for mobility impaired users who are unable to interact readily with mobile phones and PDAs or other ICT systems). Indoor localisation systems based on wearable smartdust allow tracking of users within buildings providing a link between the concept of the connected vehicle and the connected person. Research within the university is currently underway looking at novel indoor localization solutions (Fairchild *et al.*, 2006).

A key element of the connected environment is future pervasive traveller information (FPTI) whereby pervasive, bespoke information delivery may have a role in influencing travel behaviour and travel choices and hopefully could help affect a modal shift towards public transport, particularly if the cost and carbon costs of the alternatives can be readily compared. Moreover such pervasive information may also be a driver in making more effective use of DRT (Demand Responsive Transport) and flexible transport services.

Significant research is required to fully realise the potential of such wireless systems, not just on the transport application side, but challenges to reduce the size of these devices from 'smart-lumps' to 'smartdust' is critical as size, cost and power consumption of these devices will dictate whether the devices will become pervasive in the transport domain. This requires detailed work on antennae design, an investigation as to which is the most appropriate communications frequency, 802.11x, the influence of CALM (a range of connected communications standards) (chapter 9 of Pickford and Blythe, 2006), WiFi and probably the most important challenge being battery power requirements (using power scavenging or other techniques).

The final key area of research which is still embryonic is in low-cost and robust sensor design – much work is on-going but uncoordinated in the transport domain. The robustness and dependability of mobile sensor devices, suitable communications protocols and e-science techniques to deal with the data are crucial. Also important is the issue of privacy and data protection in a potentially all-seeing, all-knowing connected world, which raises the question of how much information we want, need and what level of intrusion are we willing to bear.

This section has attempted to provide a glimpse of what wireless ITS may deliver to the transport sector in the near future. We have the opportunity to bring these technologies to bear to help meet the challenges of congestion, logistics, climate change and sustainability, as eloquently outlined recently in the recent Stern Report (Stern, 2006) and Eddington Review (Eddington, 2006) in the UK.

CONCLUSIONS

The paper has presented on-going research being undertaken to investigate the suitability of using mobile ad-hoc sensor networks and motes for road to vehicle communications applications. Several projects are currently demonstrating applications of the technology in the ITS domain. The project team has presented a selection of the results from experiments carried out to systematically characterise the networks and their performance in the road domain.

Initial results suggest that both the motes and the conceptual MANET can support road to vehicle communications. However there are some significant impairments to performance due to the location and relative positions of the roadside and vehicle-mounted motes. Nevertheless, the ability to communicate between vehicle and roadside illustrates that well designed networks will enable efficient and discrete communications between vehicle and roadside – as the unit cost of motes will continue to go down – this is a significant contribution to the ITS domain.

Moreover, the paper has presented a wide range of ITS related projects that use motes for a diverse suite of applications. This, coupled with other emerging technologies introduced in the penultimate section of the paper highlights the opportunity to move towards a much more connected world for the traveller, where vehicles, the infrastructure and the traveller itself are much more connected together. If supported and developed in the correct way, this will eventually offer a steep change in how we manage, sense and operate our transport networks of the future.

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REFERENCES

ASK-IT (2007). "ASK-IT Project", http://www.ask-it.org/.

ASTRA (2005). "ASTRA Project", http://research.cs.ncl.ac.uk/astra/.

Blythe, P.T. (2006) Intelligent Infrastructure: A Smart Future with Smart Dust and Smart Markets. *Proceedings of IFAC Conference on Transport automation and Control,* Delft, August.

Blythe, P.T., Bell, M.C., Sharif, B. and Watson, P. (2006). "Pervasive Environmental Monitoring using Smartdust: The MESSAGE Project", *Proceedings of IET Seminar on RFID and Electronic Vehicle Identification*, Newcastle, November.

Blythe, P.T., Tully, A. and Martin, G. (2005). "Next Generation Wireless Technologies to Deliver Personalised Road User Charging and other ITS Services", *Proceedings of 12th World Congress on Intelligent Transport Systems and Services*, San Francisco, USA, November.

Cena, G., Valenzano, A. and Vitturi, S. (2005). "Advances in automotive digital communications", *Elsevier Journal on Computer Standards and Interfaces*, 27(6), 665 – 678.

Crossbow (2007). "MPR/MIB User's Manual", available from http://www.xbow.com/Support/Support_pdf_files/MPR-MIB_Series_Users_Manual.pdf.

Eddington, R. (2006). "The Eddington Transport Study", UK Department of Transport, available from http://www.dft.gov.uk/about/strategy/transportstrategy/eddingtonstudy/.

Edwards, S.J; Blythe P.T. (2004). "Providing Knowledge-based and Integrated Services for Mobility Impaired Users: The ASK-IT Project", *Proceedings of the 11th World Congress on ITS*, Nagoya, October.

EMMA (2007). "EMMA Project", http://www.emmaproject.eu.

Fairchild, R.G. (2004). "Applications of Wireless Devices in Transport", MSc dissertation, Newcastle University.

Fairchild, R.G., Fowler, C. and Wagner, J. (2006). "Indoor Localisation Using Wireless Sensor Networks", *2nd International ASK-IT Conference*, Nice, France, 24th October.

Foot-LITE (2007). "Foot-LITE Project",
    http://www.ceg.ncl.ac.uk/research/transport/projects/footlite.htm.
Foresight (2006). "Intelligent Infrastructure Systems",
    http://www.foresight.gov.uk/Previous_Projects/Intelligent_Infrastructure_Systems/
Geihs, K. (2001). **"**Middleware challenges ahead", *IEEE Computer*, 34(6), 24 – 31.
MESSAGE (2007). "MESSAGE Project", http://research.cs.ncl.ac.uk/message/.
Pickford, A.W. and Blythe P.T. (2006). "Road User Charging and Electronic Tolling",
    Published by Artech House, ISBN 1-58053-858-4.
Selvarajah, K. and Tully, A. (2007). "Smartdust and ZigBee for Transport Applications",
    Proceeding of the 1st European ZigBee Developers' Conference, Munich, Germany, June.
Sharif, B.S., Blythe P.T., Almajnooni, S. and Tsimenidis, C.C. (2007). "Inter-Vehicle Mobile
    Ad-Hoc Networks for Road Transport Applications", *Proceedings of IET Journal of ITS*,
    1(1), 47 – 56, March.
Stern, N. (2006). "Stern Review on the Economics of Climate Change", UK HM Treasury,
    available from http://www.hm-
    treasury.gov.uk./independent_reviews/stern_review_economics_climate_change/.
TRACKSS (2007). "TRACKSS Project", http://www.trackss.net.
Tully, A. (2006). "Foresight Intelligent Infrastructure Systems Project: Pervasive Tagging,
    Sensors and Data Collection", available from
    http://www.foresight.gov.uk/Previous_Projects/Intelligent_Infrastructure_Systems/Reports
    _and_Publications/Intelligent_Infrastructure_Futures/Reviews/Tagging_Sensorsa.pdf.
Zigbee Alliance (2007). "Zigbee Alliance Home Page", http://zigbee.org/.