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Investigation of the Applications of Smartdust for Intelligent transport Systems

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Abstract: The use of small, low-cost wireless sensors in both static and mobile ad-hoc networks has the potential to deliver a new generation of systems for the sensing, management and control of the road transport network. Low-cost and small size suggests these devices, often known as smartdust could deliver a vision for a pervasive intelligent ITS infrastructure in the near future. Based upon technical developments and the establishment of an experimental wireless network at Newcastle, this paper considers some of the technical challenges that need to be tackled to deliver this vision and also suggests a range of applications that such a network could be used for.

1. Introduction

This paper will provide an overview of research undertaken at Newcastle University on the likely application areas that small, wireless sensing devices may offer to the transport domain.

Clearly, at this stage the of the development of the wireless sensors, they exist only as prototypes and some early commercial systems whose packaging typically makes them the size of a matchbox, or what we have coined ‘smart-lumps’.

It is important to consider a ‘leap of faith’ when considering Smartdust motes for future transport applications, as at the moment the technology is fairly large with high power consumption and limited functionality. Nevertheless with the inextricable improvements in electronic circuit miniaturisation, better antennae design, and hopefully corresponding improvements in battery size, performance and the devices power consumption, one should consider what wireless motes could offer to future transport services.

1. Assumptions and Setting the Scene

The market and technical studies undertaken within the DfT Funded ASTRA project have delivered at times, some insight into how the technology may evolve. It should be highlighted that at times these areas of study have not been too detailed – rightly so as the market is evolving at times information on future developments has to be based upon supposition, wish-lists and interpreting market-hype into something realistic and useable for the transport sector, (Blythe, 2005).

2.1 Wireless and Infrared Communication Motes

Clearly Smartdust is evolving, from a communications point of view along two parallel paths, those that will utilise wireless RF communications and those that utilise infrared communications. For the purpose of this study of transport applications, it is proposed that the study focuses on the wireless, rather than infrared forms of communications – as this reflects the types of devices that Newcastle have been experimenting with for a number of years now. Moreover from the transport sector-specific view, wireless is the dominant technology for intra-vehicle, vehicle to infrastructure, infrastructure to infrastructure and
vehicle or infrastructure to pedestrian/traveller systems. As a proviso for this, it is worth mentioning that infrared motes will most likely have a role to play in static infrastructure to infrastructure communications for motes (i.e. for example static motes fitted to lampposts and other street-side furniture).

2.2 Application Classes

Capabilities and functions
When brainstorming the application areas of Smartdust motes it is clear that the potential application areas are quite wide, however with a decomposition of functionality, these devices can be re-defined into three broad categories of how the technology will evolve:

- Communications devices;
- Sensor devices;
- ID and payment devices.

The division of the sensors will be sub-divided again by location and functionality, for road transport and infrastructure, one would suggest:

- In-Vehicle;
- Vehicle to Infrastructure;
- Infrastructure; and
- Personal/individual devices (which would incorporate the ID and payment categories.

Application Sectors

In terms of sector specific application areas within the transport domain, the initial list of application areas covered all transport major sectors, namely:

- Individual/pedestrian;
- Road;
- Rail/LRT;
- Freight;
- Air; and
- Waterborne.

On further consideration and reflection of the field, it was decided to focus this report on applications within the road and individual/pedestrian domains. It is important to state here that the research team recognises that there are a whole myriad of applications outside of the these specific two sectors, however of greatest interest at the moment is how these wireless systems and the various motes that may evolve could be used to support future intelligent infrastructure – which is the subject of an OSI-Foresight project at the moment. Central to its goals is the view that increasing the level of intelligence in the infrastructure, coupled with increased sensing, processing and communications capabilities on both vehicles and travellers/pedestrians may lead to new paradigms in how the transport network is managed, controlled and operated in the future. Indeed, vehicles, pedestrians and infrastructure, fitted with wireless motes could communicate and cooperate with each other to improve the safety, efficiency and management of the transport network as a whole. Moreover, future decisions as to whether to invest in new physical infrastructure (concrete, tarmac and steel) or in more effective use of the infrastructure by investing in new intelligence is a policy challenge that will require to be addressed soon and indeed forms part of the foresight study (www.foresight.gov.uk). In addition to this, the ability to possibly charge travellers in a more pervasive way for the travel they make and possibly the environmental footprint that they create with their journey – could indeed form part of future policy thinking, if the fairly dire warnings on future energy availability, the effect of green house gasses and future climate change, the are included in the foresight study are not heeded.

3.3 Future Smartdust Capabilities
To review future applications of Smartdust/motes technology, it is necessary to make certain assumptions as to what the technology will be capable of in the future and indeed the necessary robust security protocols and dependability will be delivered for such networks (Shi and Perrig, 2004).

To be realistic we can never completely predict the future, however for the purposes of this review we will make the following assumptions as to how the technology will evolve. These assumptions are taken from the future scoping review of the technology and also based upon the practical trials and testing of current generation Smartdust and motes at Newcastle University (http://www.ceg.ncl.ac.uk/research/transport/projects.htm).

From a technical viewpoint there are many issues to be considered, however the authors suggest that to be practical in terms of what may be available in the future, it must be assumed that these technical issues are tackled in some way. These four primary issues are:

**Battery life and size.** At present the battery size is an overriding reason why we are using ‘smart-lumps’ rather than ‘smart-dust’. The motes require an on-board power source to sense the network, operate the processing and communications functions and support wake-up protocols. In very simple RFID circuits, these devices may be completely passive and derive their necessary electrical power from the incident signal generated by the interrogating device. This is not really feasible for Motes as they must form ad-hoc networks with other such devices, thus the incident power from another device (unless it is a dedicated ‘interrogator device’), would not be sufficient to power the mote. In other ASTRA reports the move towards power scavenging and low power circuitry suggest that the size of the ‘battery’ or ‘power conversion and storage’ device will reduce, as will the power consumption of the mote itself, as the systems are miniaturised and integrated. In the transport application domain there will be requirements for different classes of motes, whose power requirements and availability will be somewhat dictated by where the device is sited, whether it be static or mobile, its performance characteristics and functionality, the mote’s physical size and any payload connected to it (i.e. a sensor load). It will be assumed that future devices will have the necessary power available to support their functionality.

**Antenna.** For wireless motes (which are the only genre now being considered here), the size and sensitivity of the antennae remain an issue. Current generation motes generally use a mono-pole or dipole antennae which is a couple approximately 5 cm long (at 2.45GHz frequency band) – this is to some extent constrained by $\lambda/4$ constraint which requires the minimum physical size of the antenna for efficient reception and transmission to by one quarter of the wavelength of the carrier signal (in the particular dielectric medium of the ether). Adaptive antennae designs may overcome this – as may microstrip antennae fabrication techniques, which enable small-size, conformant the antenna to be printed on some high-dielectric circuit board substrate). The antenna of future motes will be configured to suit the appropriate operating environment, in terms of size, power requirements and communications range (and beam-forming capabilities, if directional antennae are required). Moreover, it is anticipated that RF circuits will require less power to operate with a lower S/N ratio and receiver sensitivity.

**Communications protocols.** The third technical area where mote technology is lagging is in the communications protocols used to form the ad-hoc networks (be them static, mobile, or a combination of the two). The dependability and robustness of these protocols to operate in environments where noise and signal blocking may not offer an ideal operating environment, coupled with the challenge of dealing with numbers of motes and semi-random nature the data they wish to pass on and exchange challenges current generation protocols (Culler and Hong, 2004). It is assumed that within a 5 year timetable these challenges and shortcomings will be sorted out to a large degree and should not overly impede the implementation of
MANET networks in the transport environment. However with any wireless communications system – it should be noted that communications and protocol performance will never be 100%. Nevertheless, built in redundancy, dependability, error recovery and other robust strategies can be developed to mitigate these vagaries.

Size of Motes. It may be assumed that the size of the motes will reduce significantly within 5 years. Obviously motes will different functionality may be different sizes by necessity, i.e. a controller/router mote will be larger than a simple sensor mote. It is conceivable that if battery and antennae technical design problems are solved the size of the smallest (and lowest level functionality) motes could be a few mm² within this time period (Hill, 2005).


3.1 Applying Framework to Smartdust Applications

The design of a smartdust device has a generalised operating procedure, using an input from its local environment, performing some form of processing and supplying an output which may be fed back into the environment. This can be summarised in the diagram below.

Figure 1. Generalised smartdust operating characteristics

When considering a real world problem, the information flow can be represented as an output generated from an input. This representation involves three modules, the request, the processing and the output. The connections between each module can be thought of as separate stages as they may require an external device to implement. The request connection (stage 2) and the output connection (stage 4) can be formed by any communications link. This therefore means that the real world problem can be broken down into five stages;
Stage 1: Request stage, provides input into the processing module, the request stage may be a sensor or an input device such as a wireless collection.
Stage 2 & 4: This connection stage may be any physical link, or device.
Stage 3: Performs the processing, this maybe making a decision dependent on the input data or assimilating data for further usage.
Stage 5: This module may actuate a mechanical device or sending data onwards.

3.2 Operating Characteristics

The smartdust operating characteristics can be applied to the general solution, providing a “single box solution”, where the smartdust sensors formulate the request that is sent to the onboard processor to create an output.

However, as smartdust devices are infinitely configurable, it is possible that they could perform any of the tasks within the general solution. For example, a smartdust device may only be a sensor that supplies information to a remote central processing system, performing only stages 1 and 2. Or, the smartdust device may be part of a mesh network simply providing a pathway from a sensing device to a processing device or from a processing device to an output – stage 2 or 4.

Thus it follows that any problem that can be expressed by the general solution can be solved exclusively or partly with smartdust devices.

4. Potential Applications of Smartdust in Transport

4.1 Applications

Four broad categories exist within the transport industry to which smartdust devices can be applied; in car applications, vehicle to infrastructure, infrastructure and personal devices. An MSc dissertation (Boireau, 2005) which provides additional information and thoughts on many of these application areas,

The list below proposes several applications within each category that smartdust can be applied. Following the list are a more detailed example from each category.

In Car Applications
- Theft detection
  Smartdust sensors detect unauthorised movement of vehicle containing a reciprocal smart sensor and inform a control centre via a communications link.
- Drive by wire
  - Accelerator
  - Brake
  - Clutch etc.
  These examples show how smartdust devices can replace traditional connection by wires in a motor vehicle. When the control device is actuated, the smartdust forms the link to another smartdust device on the output device, e.g. connecting brake pedal to brake pump.
- State sensors
  - Tyre pressure
  - Tyre tread depth
- Brakes
- Coolant level
- Oil level
- Brake fluid
- Windscreen washer fluid
- Oil temp etc.

Using smartdust as the sensor to detect pressure, liquid level etc., and retransmitting this to the car’s central computer, the user can be alerted to any dangerous situation requiring attention. For example smartdust embedded in tyres would wear away, once no devices were left in the tyre it would alert the user to replace the tyre. Moreover, since many devices could be embedded in the rubber, an estimation of the remaining useable distance left, uneven wear alerts and tyre temperature can all be modelled and reported.

**Vehicle to Infrastructure**

- **Fast flow tolling**
  Using smartdust devices in place of the more standard microwave transponders, it is possible to create a fast flow tolling system built up entirely of smartdust.

- **Congestion charging**
  Smartdust can be used to define the geographical boundaries used in a congestion charging system. Smartdust can be embedded in street furniture or in the white paint on the road surface. When the user's smartdust equipped vehicle passes over the sensors the user's account is charged accordingly.

- **Network state reporting**
  - Speed
  - Number of vehicles
  - Traffic flow and density reporting
  - Temporary measurement sites
    Using smartdust within a connected, distributed network, the state of the road network can be monitored remotely, allowing traffic controllers to perform access control to motorways and alter traffic light sequences with live response. The smartdust would be embedded in the road with magnetometers or pressure sensors to detect vehicle presence.

- **Local area information provision**
  - Tourist attractions
  - Parking places
    As a user enters the city boundaries, their smartdust enabled device or vehicle can communicate with roadside smartdust devices to receive information about the local area and book a parking space etc.

- **Fleet position reporting**
  Smartdust enabled vehicles within the connected city can be tracked and traced allowing fleet managers to report their positions to variable signs for public transport information or to a control centre for vehicle and freight security and quicker dispatch of emergency services.

- **Parking space occupation and payment**
  Smartdust embedded in parking spaces can detect if they are in use or not. This means that accurate space reporting can be relayed to remote users via internet or onto variable signs, this setup would also allow users to be allocated spaces and security alerted to the presence of an unauthorised vehicle.

- **Emergency green wave**
  Smartdust equipped emergency vehicles can trigger a green wave by switching the ahead traffic lights green when trying to negotiate busy city traffic.

- **Smart traffic calming**
  Vehicles that are travelling below a certain speed can trigger the calming measures to reduce their impact. For example air filled speed humps can have a valve that allows the air to be released when a vehicle passes over it,
but a speeding or unequipped vehicle would negotiate the hump as if were solid.

A report from Fairchild on experimentation undertaken at the University on road to vehicle communications performance of smartdust – covering some of the application areas mentioned above. (Fairchild, 2004)

**Infrastructure**

- **GNSS Signal correction provision (SiSNet, DGPS, WAAS etc.)**
  
  Corrections for GNSS are regional, meaning that a citywide area could be supplied with the same corrections giving better accuracy for GPS and Galileo users. Smartdust can be equipped to communicate to GPS/Galileo devices or PDAs and smartphones that might have GPS software onboard.

- **Distributed environmental monitoring**
  
  Sensors detecting pollutants can be embedded onto a smartdust device as part of a distributed network and can relay environmental information to a central location. Controllers could deny access to the city centre to vehicles, or charge accordingly for entrance/transit based on pollution (Blythe, Bell et al, 2006).

- **“Smart Infrastructure”**
  
  - **Adaptive street lighting**
    
    Street lights could be made more independent for switching on and off, or could adapt their output depending on the ambient light levels, using smartdust for sensing and processing.

  - **Smart street furniture**
    
    Street furniture with smartdust sensors onboard can be used to detect bins that are full or unauthorised removal of objects such as signs or enforcement cameras.

- **Accident detection**
  
  - **Barriers**
  
    Barriers that are breached or removed from position can be used to detect accidents. The smartdust network would be able to relay the position of the crash immediately to a remote controller. This system would be especially useful in remote areas and late at night.

- **Personal localisation for indoor areas**
  
  Using a smartdust network to create a personal locating system for indoor use would allow indoor mapping to be used by visitors to large exhibitions or museums and would allow infinite customisation by users including mobility impaired users who require information on an accessible route and accessible facilities.

- **Emergency locating devices**
  
  The indoor smartdust localisation network can be set to display the position of all users that require assistance when the building emergency alarm is activated.

- **Provision of value added services**
  
  Because of the ability of smartdust to use any communications technology available, they can be used as an access point for data bearing services such as video calling, traffic news or on demand media.

- **Smart signage**
  
  Smartdust can be used to collect or retrieve data for signs as well as collect other data such as the ambient light levels to determine illumination levels.

**Personal, ID and payment devices**

As part of device that a user consistently carries around with them, such as mobile phone, watch or even embedded in jewellery, smartdust can be used to identify an individual and use this information to provide services dependent on settings pre-recorded earlier. Keyless entry can be achieved as well as using the devices to pay for entry onto public transport.

- **Payment / prepayment / account payment**
  
    - **Public transport**
4.2: Extended Description of Selected Applications

Using the methodology described above in section 3, a 5 stage description of one application from each application category is provided to illustrate how the methodology could be applied in practice.

**In car applications**

Drive by wire involves the use of two wireless devices to provide the input from the driver on the steering wheel or brake pedal and output the turn direction to the steering column or actuate the hydraulic brake pump. The general solution can be applied to drive by wire applications:

Stage 1: Driver input
Stage 2: Communications link
Stage 3: Smartdust processor or car ECU
Stage 4: Communications link
Stage 5: Smartdust enabled actuator

Expanding the general solution for the case of the brake pedal;

Stage 1: Driver presses brake pedal smartdust device senses the amount of pressure
Stage 2: Wireless transmission to the vehicles electronic control unit (ECU)
Stage 3: ECU performs processing
Stage 4: Wireless transmission to smartdust enabled brake pump
Stage 5: Brake pump actuated, brakes applied

**Vehicle to Infrastructure**

Fast flow tolling requires either the vehicle or the toll system to sense that the vehicle has past the toll barrier and charge the users account accordingly. This system may take a positional input from a satellite positioning receiver and compare with an internal map. Or smartdust maybe embedded into the road or positioned on a barrier over the road, creating a connected network as the vehicle passes through the barrier.

The smartdust may perform the accounting function or may simply pass the information via another communication protocol such as GPRS or VHF to a central server.

Using smartdust in this way conforms to the general solution presented earlier.

**Infrastructure**

Environmental monitoring can be used as part of a road user charging system where the charge for driving on a particular section of road is scaled according to the current pollution levels.

This kind of system would need real time monitoring of the environment surrounding a road network. This could be achieved by distributing smartdust along the road. The smartdust would be equipped with sensors to measure Carbon Monoxide, Hydrocarbons and / or Nitrous Oxides. The levels of the pollutants can be averaged out along the road network and a charging rate deduced.
Personal ID and Payment Devices

Payment for public transport services is archaic involving the user to need enough cash in small denominations to pay for the ticket. Schemes such as the London Oyster Card are embracing new technology, allowing the user to prepay the Oyster account and use the card to access any public transport system within the Transport for London Remit.

Smartdust would provide extra functionality not provided by the Oyster card. The Oyster card requires the user to swipe the card over a reader before boarding the train. A smartdust scheme would allow the users payment smartdust device to form part of the public transport network, at the top or platform or whilst onboard the vehicle. Benefits of a smartdust system are many. The seamless payment system means that the smartdust payment card can be kept in a bag or pocket, freeing the user’s hands for carrying luggage. The fleet manager of the transport system would also know exactly how many passengers are on board the vehicle, allowing better network management.

5. Summary

The opportunity to harness the potential of new, intelligent infrastructure within the road transport sector will be a major research issue of the next decade. The ability to monitor, sense, manage and communicate with vehicles, the roadside control systems and the driver offers new and currently unexplored tools to manage the road network more efficiently. If the technology develops in a beneficial and coordinated way there are real opportunities for the UK to lead in this area of ITS development.

Building on the research at Newcastle University on wireless sensor networks and pervasive information delivery, we feel that there is an urgent need for coordinated research in the UK that will fill in the research gaps in pervasive, mobile adhoc 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 (as on-going in the EU TRACKSS project) and also connected to individuals through their PDAs, mobile phones, or even bespoke wearable interfaces (in the EU ASK-IT and Future Pervasive Information projects at the University) offer potential for a more all-seeing, all knowing ITS infrastructure. If for example, vehicles are continually in wireless communication with the infrastructure (through small wireless sensors embedded in 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 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 so 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 occupancy or blue badge entitlement.

Although this is an potentially exciting and significant new technology area for transport, we are at the beginning of the technological and application-related research in this area, however the opportunity to use these devices to deliver a future intelligent infrastructure for transport as envisaged by the Foresight Intelligent Infrastructure Study (www.foresight.gov.uk) and (Blythe, 2006) is a challenge that needs to be met. Significant research is required for 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 and cost 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, 802.11xx, the influence of CALM, 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 and not necessarily influenced by the transport domain (although the recent submission to
EPSRC for Pervasive Monitoring of Environmental Sensor Grids, PMESG, will hopefully help to bridge this gap. Finally the robustness and dependability of mobile sensor devices and suitable communications protocols and e-science techniques to deal with the data are crucial. As is the issue of privacy, data protection in a potentially all-seeing, all-knowing connected world and how much information do we want, need and the level of intrusion – are all challenges that need research in the interface between policy, technology and society.

If these issues are addressed and resolved in an appropriate way, then the opportunities for smartdust as part of wired is connected world for future transport is high – and will also help the DfT deliver the vision of intelligent infrastructure envisaged by the Foresight project.

6. References


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