Speckled Computing: Disruptive Technology for Networked Information Appliances

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Abstract — *Speckled Computing is an emerging technology in which data will be sensed in minute (ultimately around one cubic millimetre) semiconductor grains called Specks. Information will be extracted, exchanged and processed in a collaborative fashion in a wireless network of thousands of Specks, called a Specknet. The impact of Speckled Computing on consumer electronics, especially future information appliances, will be disruptive. Objects and the surrounding environment when treated with Specks, or "Speckled", will be endowed with sensing, processing and wireless networking capabilities. This would effectively "smarten" everyday objects and surroundings post hoc, transforming them into networked information appliances. This paper introduces the concepts of Specks, Specknets and Speckled Computing, and outlines the challenges to be overcome to realise this technology. A prototype for Specks called ProSpeckz (Programmable Specks over Zigbee Radio) which is currently used as a rapid development platform for Speckled Computing is described. ProSpeckz is also intended as an enabler for integrating the technology of Speckled Computing into consumer electronics applications and some illustrative examples are described in this paper.*

Index Terms — Networked Information Appliances, Smart Home applications and protocols, Speckled Computing, Wireless computational networks

I. INTRODUCTION

A Speck is designed to integrate sensing, processing and wireless networking capabilities in a minute (ultimately one cubic millimetre) semiconductor grain. Specks are intended to be autonomous, each with a renewable energy source, and can be mobile if needed. Thousands of Specks, scattered or sprayed on any person or surface, will collaborate as programmable computational networks called Specknets. Computing with Specknets, or Speckled computing, will enable linkages between the material and digital worlds with a finer degree of spatial resolution than hitherto possible. Specknets are intended to be a generic technology for ubiquitous computing, where data is sensed, processed and information extracted in situ in a collaborative fashion.

Speckled Computing is the culmination of a greater trend in consumer electronics. As the once separate worlds of computing and wireless communications collide, a new class of information appliances will emerge. Where once these appliances stood proud; the PDA bulging in the pocket, or the mobile phone nestling in one's palm, the post-modern equivalent might not be explicit after all. Rather, data sensing and information processing capabilities will fragment and disappear into everyday objects and the living environment. At present there are sharp dislocations in information processing capability; the computer on a desk, the PDA/laptop, mobile phone, smart cards and smart appliances. In our vision of Speckled Computing, the sensing and processing of information will be highly diffused; the person, the artefacts and the surrounding space become at the same time computational resources and interfaces to those resources. Surfaces, walls, floors, ceilings, articles, and clothes, when sprayed with Specks (or "Speckled"), will be invested with a "computational aura" and sensitised post hoc as props for rich interactions with the computational resources. Given their minute sizes, Specks will have the ability to bring sensing and computation to places hitherto unreachable and wireless communication will enable Specknets to be the first (last) millimetre of the world-wide web. We predict that the impact of Speckled Computing on consumer electronics will be truly disruptive.

II. SPECKS AND SPECKNETS

Fig. 1 gives a system-level overview of the individual Speck and the Specknet. It is intended that Specks will be programmable, with the Specknet operating as a fine-grained distributed computation network, employing a lightweight and power-conscious communication protocol. The means of wireless communication will be a combination of optics (for example, laser and infrared) and radio, each with its strengths and weaknesses. Whereas optical communication is unidirectional, the radio communication is omni-directional; although optical communications consume several orders of magnitude less energy than radio, they are susceptible to breaks in communication due to occlusion or movement.

Specknet presents unique networking problems that will demand novel solutions. This is networking at its extreme and some of the key features of the Specknet will be decentralised control and adaptability. Adaptability is manifest in several ways, such as: dynamic routing to account for loss of connectivity either due to communication failures or the expiry of Specks; a power-sensitive Medium Access Control (MAC) layer which is aware of power depletions in a Speck and adapts the computation and communication accordingly; a combination of redundant processing and Speck bypassing within a group of Specks.

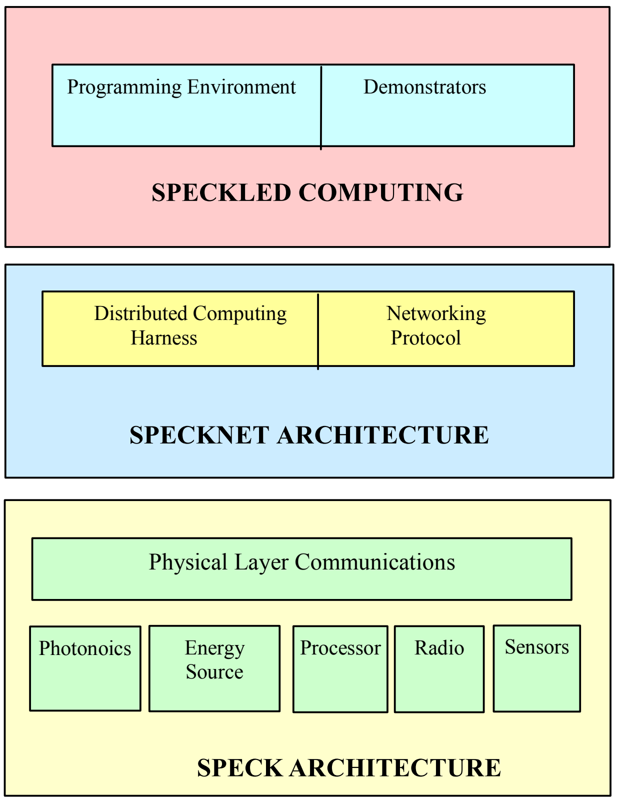

Fig. 1. System-level Overview

The Speck, though modest in terms of processing and storage resources, can be powerful as part of a collective system when harnessed as a Specknet. Specks would process their own sensor data and report only results and summaries externally. Limited individual processing power implies that Specks would need to organise the required processing collectively within a Specknet. Thus, a new model of distributed computation is being developed which will take into account some specific attributes of Specknets, such as unreliability of communication, a higher than normal failure rate of Specks due to harsh operating environment and very large volume manufacturing.

III. PROSPECKZ – A SPECK PROTOTYPE

ProSpeckz ("Programmable Specks over Zigbee Radio") is a prototype (Fig. 2) to enable both the rapid development of Specks and provide academia and industry with a platform to develop new applications for this emerging technology.

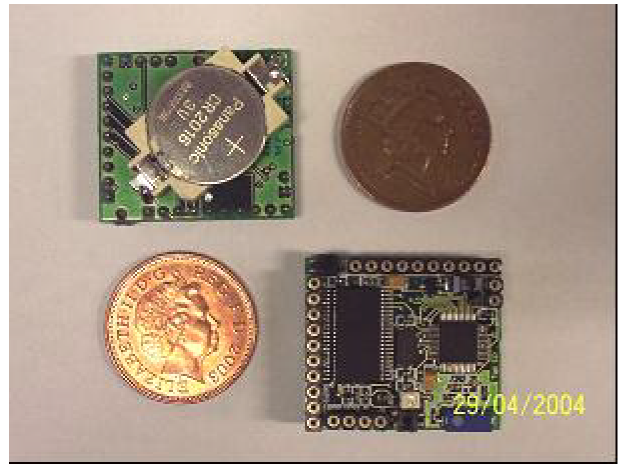

Fig. 2. The ProSpeckz compared to a British two pence coin

ProSpeckz provides the researcher with a means to determine the constraints and parameters in the real world which will inform the design of the semiconductor Specks and validate the simulation models that would be developed for Specks and Specknets in the future. It can also be incorporated, albeit with a form factor larger than the proposed Specks, into prototypes of future products for functional verification of the design.

ProSpeckz uniquely combines the following components into a versatile development platform:

a. An 802.15.4 compliant [1] radio chipset provides wireless communications up to data rates of 250kbps over 16 channels.
b. 2.4GHz matched antenna and filter circuitries allow software adjustable ranges from 30 centimetres to over 20 meters.
c. A Programmable System-on-Chip [2] (PSoC) enables ProSpeckz to provide software reconfigurable analogue circuitries to external interfaces and components. The PSoC is also the processing core of the ProSpeckz providing an 8-bit micro-controller with 16Kbytes of FLASH and 256bytes of RAM.

The systems overview of the ProSpeckz, which is constantly in development to reflect the actual semiconductor Specks, is shown in Fig. 3. On the hardware layers, the 802.15.4 radio is used to provide for physical wireless communications while the analogue re-configurability of the PSoC allows for the easy integration of sensors and actuators on the ProSpeckz. On the firmware layers, a power aware Medium Access Control (MAC) layer is used to provide efficient use of the radio channel via duty-cycling. It also manages the channel allocation to provide contention free access whenever possible.

A novel lightweight Specknet network protocol handles the routing between Specks using a unicast or multicast approach. This provides the higher layers the capability to wirelessly transmit data across the Specknet easily.

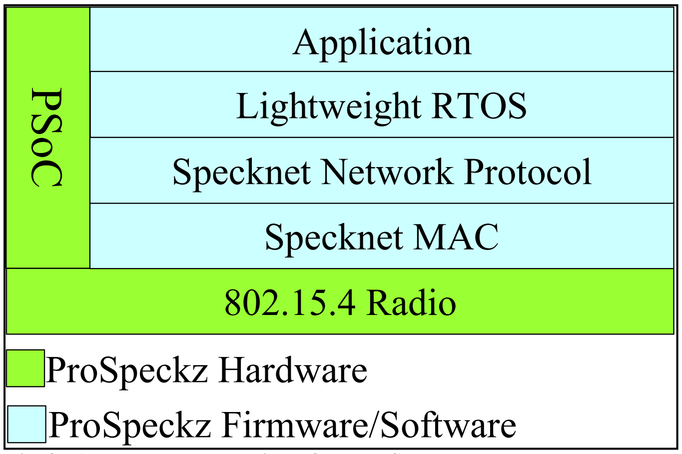

Fig. 3. A system-level overview of the ProSpeckz

A lightweight real-time operating system provides device drivers for the sensors and actuators connected to the board as well as allowing the scheduling of tasks, events and commands. A virtual machine could be implemented alongside the operating system to ensure interoperability for application developers as well as allowing for the easy development of simulation tools for the ProSpeckz. The virtual machine is intended to provide isolation between the hardware layers and the application program such that programs can run with least intervention between different versions of ProSpeckz.

Finally, the power consumption for the ProSpeckz in different modes is displayed in Table 1.

ProSpeckz Operational Modes	Consumption
Radio and PSoC in Sleep State	1mW
PSoC Running, Radio in Sleep State	17mW
PSoC, Radio Oscillator and State Machine Running	19mW
Data Transmission at:	
0 dBm	80mW
-5 dBm	68mW
-10 dBm	57mW
-15 dBm	53mW
-25 dBm	48mW
Data Reception	88mW

Table 1. Power consumption of the ProSpeckz in different modes

IV. Deployment of ProSpeckz in Consumer Electronics

The re-configurability of the ProSpeckz enables it to be interfaced easily to existing consumer electronics appliances such as televisions, hi-fi sets, and video recorders. The analogue circuitry on the ProSpeckz can be easily changed under software control to allow one hardware implementation to be used across multiple application domains. For example, using the PSoC Design Developer from Cypress Microsystems [2], the applications designer could easily reconfigure the 16 interface pins provided by the ProSpeckz to provide the following components:

a. Analogue Components
Programmable gain amplifiers, programmable low-pass or band-pass filters, switched capacitor blocks, 9-bit digital-to-analogue converters, among others.

b. Digital Components
Pulse width modulators, 8 to 32 bits counters/timers, hardware cyclic redundancy check (CRC) units, 8/16/32 bits pseudo random generators, to name a few.

c. Communications Components
Universal asynchronous receiver/transmitter (UART), serial peripheral interfaces (SPI), I^2C, infrared controls (IrDA), for instance.

ProSpeckz is an ideal platform to investigate the impact of Speckled Computing in the "Smart Home" [3] and the "Smart Space" applications [4]. By connecting sensors such as heat, pressure, motion and light detectors onto the ProSpeckz, a network of them can monitor the environment in a house and react under program control to any changes. The ability to reprogram ProSpeckz "over-the-air" enables upgrades to the ProSpeckz operating system and application programs without the need to physically connect. It also allows the network to be reprogrammed instantaneously and effortlessly thus providing the ability to upgrade pervasively when new sensors and actuators are added to the network.

Finally, ProSpeckz is an ideal platform to explore the integration of Speckled Computing technology into toys. ProSpeckz, when connected to an appropriate actuator such as a motor, can be used as a mobile platform for distributed game algorithms in robot soccer [5] and seek-and-destroy games. ProSpeckz can also be placed into toys on a smart playing mat to provide an interactive narrative of story, rhymes, songs and factual information when particular toys are in close proximity or the focus of attention. These linkages between the physical and digital worlds will provide a rich source of interaction during the child's educational development.

V. Demonstrators of ProSpeckz in Action

To further demonstrate the wide applicability of the ProSpeckz, several simple applications had been built and will be discussed briefly in this section.

a. A typical sensor network application

ProSpeckz can easily be used to demonstrate possible sensor network applications. By attaching a temperature sensor on each ProSpeckz, the ProSpeckz can be reprogrammed to function as fire detectors as shown in Fig. 4. Multiple ProSpeckz are then placed around a building and they will communicate with each other wirelessly forming a distributed wireless fire alarm network. Unlike conventional wired fire alarm systems, the proposed fire system is extremely intelligent. Instead of sounding an alarm in some far away centralized fire panel when a fire is detected, the ProSpeckz will lead the people in the building away from the fire by forming a trail of running lights using the LED on each ProSpeckz as a guide. A simple distributed program onboard each ProSpeckz enables them to coordinate in a distributed matter in order to display the trail. Furthermore, unlike conventional wired system where the fire would potentially burn away the wires, ProSpeckz communicate wirelessly and the system would still be functional even if some of the ProSpeckz are destroyed by the fire.

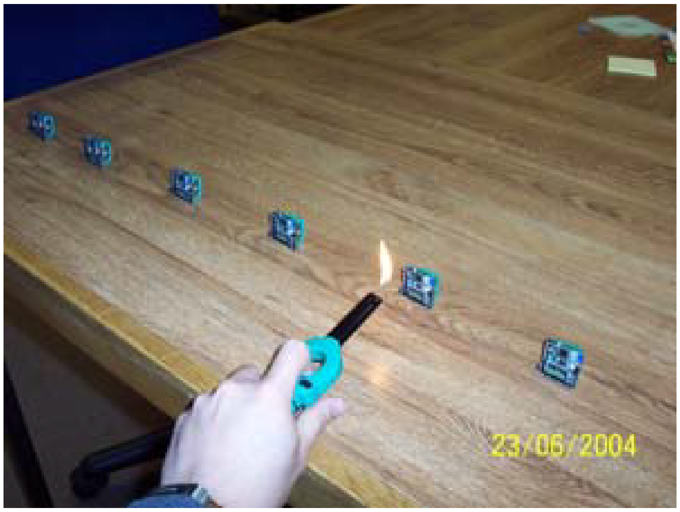

Fig. 4. Demonstrating a distributed intelligent wireless fire alarm system

b. A test bed for developing distributed algorithms for Speckled Computing

As discussed earlier, one of the main usages of the ProSpeckz is to assist the development of algorithms for Speckled Computing. An example of such algorithms is a distributed algorithm for logical location estimation. This algorithm allows each node in a wireless network to estimate its own logical position based on its two-hop neighbour information. A logical position is defined as a coordinate in a two or three dimensional plane that is relative to the logical positions of the other nodes. Thus, a set of logical locations would give the layout of the nodes without the physical effects of rotation and translation. Logical location information is extremely important in most sensor network applications as the location information about where the data is sensed is deemed almost, if not, as valuable as the sensed data itself.

The algorithm has been designed and simulated on a Java software platform and is seen to be functional. However, there is a need to fully test out the algorithm in the physical world. This is where the ProSpeckz plays an important part. Each ProSpeckz is interfaced with a liquid crystal display (LCD) module (as shown in Fig. 5) which allows real-time readout of essential data on each node like the estimated logical location and the number of neighbours each node can communicate directly with. By moving the ProSpeckz about we can now determine, via the readouts on the LCD, the feasibility of the algorithm in real-life physical implementation and derive ways of improving it so as to achieve more accurate and stable estimations quickly.

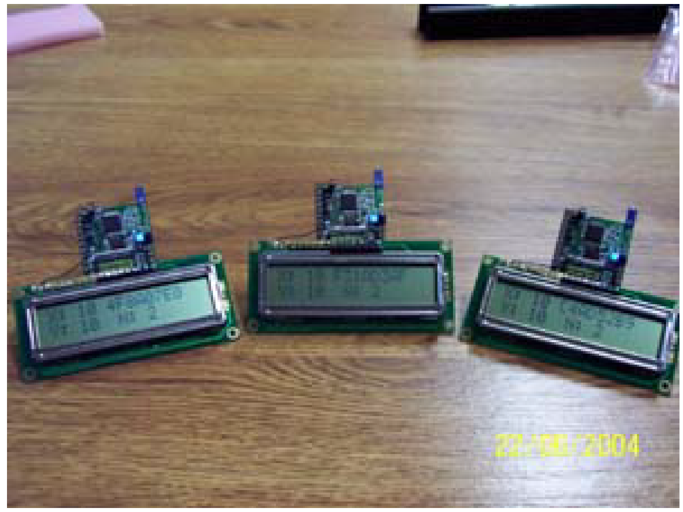

Fig. 5. Demonstrating ProSpeckz to test, develop and experiment with distributed Speckled computing algorithms

c. A platform to discover and develop novel consumer applications

The ability to easily interface to sensors and actuators commonly used in consumer electronic appliances allows the ProSpeckz to be utilized effectively in the search for a novel consumer application. For example, in Fig. 6, a speaker and an infrared range detector is connected to the ProSpeckz. Based on the measured distance between the ProSpeckz and an object (for example, a hand), a different note is played on the speaker. One could imagine the use of this as a "keyboard-less" musical keyboard where a song can be played by the movement of the hand or body. By using several of the ProSpeckz that are placed in strategic locations, it is also possible to emulate other musical instruments, for example, a string-less harp (a harp with virtual strings).

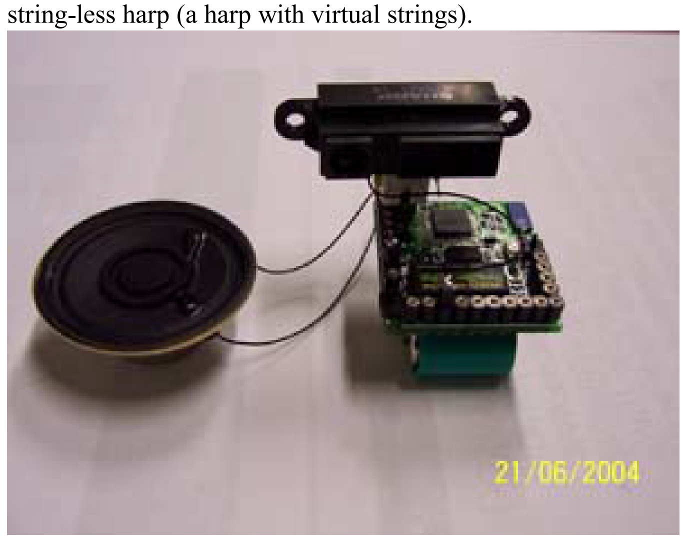

Fig. 6. Demonstrating ProSpeckz being used in the search for novel consumer applications, for example, a "keyboard-less" keyboard

d. A generic technology for mobile toys and robotics

A possible area of exploration for Specks is the use of actuators such as motors to allow mobility of the Specks. This could be made possible on the minute Specks via microelectromechanical system (MEMS) actuator arrays as used in the design of a walking silicon micro-robot [6]. However, to investigate the algorithms and applications in the absence of physical Specks, a ProSpeckz can be used. As shown in Fig. 7, a ProSpeckz is interfaced with a miniature car. This allows the programmer to develop applications in which multiple of these cars have to cooperate in order to achieve a certain function. Examples for such applications include mobile network routers, robotics games and mobile sensor networks.

Fig. 7. Demonstrator in which a ProSpeckz is interfaced to a miniature toy car to enable it to move in a coordinated fashion via wireless communications with other ProSpeckz

VI. CONCLUSIONS

Speckled technology can be seen as a new age of computing and its introduction to consumer electronics will be extremely disruptive, both in the ways in which new applications are built as well as in the ways which true pervasive and ubiquitous implementations are made possible. A Speck prototype, ProSpeckz, is designed to serve a dual purpose. It is intended to inform the design of the semiconductor Specks by providing a flexible platform to experiment with the firmware, networking protocols, distributed computation harness and programming environment. Secondly, it will help prospective users of Specks to develop applications which could be ported to the semiconductor Specks with minimal effort. This will allow users to specify the requirements and determine the list of attributes for the minute Specks which are essential in the early design stages of this technology.

VII. ACKNOWLEDGEMENTS

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