Homework: Shaping Future User Centred Domestic Infrastructures

University of Nottingham
University of Glasgow
Imperial College London
Georgia Institute of Technology
BT
Microsoft Research Cambridge

Part I: Investigators' Track Record

This proposal presents a novel interdisciplinary partnership between those who design 'end user' technology and interaction, and those who seek to realise future management approaches and network architectures to re-invent the domestic infrastructure from a human centred perspective. In order to do so we bring together an international team with expertise in domestic settings drawn from projects such as Equator (Nottingham) and the Aware Home (Georgia) with extensive experience in the management of digital infrastructures (Imperial), network monitoring (Glasgow) and computational models (Glasgow) drawn from a broad portfolio of existing EPSRC Projects including a number of existing WINES projects.

Nottingham University – Mixed Reality Lab

The Mixed Reality Laboratory (MRL) is an interdisciplinary lab where computer scientists, psychologists, sociologists, engineers and architects collaborate to explore the potential of ubiquitous, mobile and mixed reality technologies to shape everyday life. Research is grounded in a user-centred approach which combines expertise in interaction and distributed systems to rapidly prototype interactive technologies. Multiple evaluation techniques are used to understand how these are experienced by people 'in the wild'. Our research contributes to a variety of fields including Ubiquitous Computing (Ubicomp), Human-Computer Interaction (HCI), and Computer Supported Cooperative Work (CSCW). The MRL has evolved a distinctive approach to its research that combines:

- *Research "in the wild"* – we constantly emphasise the importance of moving out of the research lab and beyond the "cool demo" by deploying and studying emerging technologies in real-world settings including the home.
- *A multidisciplinary perspective* that combines expertise in software and hardware with knowledge of how to design engaging experiences for real people and study their experiences.
- *A focus on integration through iteration* in which the results from multiple practice-based projects undertaken in the wild are combined and generalised through reflective activities which in turn inspire further experiences.

The lab has extensive experience in large scale multidisciplinary endeavours and was coordinating partner for the Equator IRC. Following an external review by an international panel, EPSRC's final report observed *"The IRC turned a high risk starting point into something not only excellent but fundamental and which has now become main stream. The US are trying to catch up in this area where the UK is a leader and this is all credit to EQUATOR."*

Professor Tom Rodden – is exploring ubiquitous computing for everyday living, including in both the home and workplace. He has published widely in Ubicomp, HCI and CSCW and has acted as chair for the leading conferences in these areas. He directed the Equator IRC, co-directs the ESRC e-Social Science Research Node "DReSS" and has played a leading role in the establishment of UK Grand Challenge in Ubiquitous Computing. He has recently been awarded an EPSRC senior fellowship to investigate new interdisciplinary approaches to ubiquitous computing.

Dr Andy Crabtree – conducts ethnographic studies of ubiquitous computing environments in order to understand the social organization of technology-in-use and shape the design of future technologies for collaborative work. He is a sociologist by training and a newly appointed RCUK fellow. He is author of the book *Designing Collaborative Systems: A Practical Guide to Ethnography* [6] and co-directs the ESRC e-Social Science DReSS Node.

Professor Steve Benford – is exploring how Ubicomp can enable creative and artistic experiences spanning performance, games and broadcasting. He co-founded the MRL and has published over 200 works, including six papers in ACM Transactions on CHI and 18 full papers at the annual CHI conference (including a best paper award in 2005). He is currently scientific manager of the European Integrated Project on Pervasive Gaming.

Professor Chris Greenhalgh – researches distributed systems support for Ubicomp. He was awarded a BCS Distinguished Dissertation award for his PhD work on the MASSIVE system to support scalable CVEs. As a member of the Equator project he has since created two generations of the Equip platform that has been widely used to realise a variety of public ubiquitous and mobile experiences and that underpins the MRL's capacity to deliver novel experiences.

Glasgow University

The Glasgow team spans three research groups: HCI; Embedded, Networked and Distributed Systems; and Formal Analysis, Theory and Algorithms, each with strong international reputations and extensive experience of interdisciplinary collaboration.

Professor Joe Sventek – whose primary research interests over the past 25+ years have been the areas of distributed, object-oriented systems, novel measurement techniques for IP-based networks, proactive management of IP-based networks, signalling protocols for communication networks, and embedded, networked computing systems. He is a fellow of the Royal Society of Edinburgh and the IET; he is also a senior member of the Institute of Electronic and Electrical Engineers. He was the Principal Investigator at Glasgow for the EPSRC-funded projects: AMUSE (GR/S68040/01); P2POpt (GR/S68996/01); and PRISON (EP/C004442/01); he also leads the DIAS-MC Wines 1 consortium (EP/C014774/01).

Professor Muffy Calder – has a long track record in modelling and reasoning about real-world, concurrent systems, from telecommunications services, to medical devices and biochemical signalling pathways. She has developed techniques for automated detection of feature interactions in communications networks and for modelling dynamic behaviour of signalling pathways based on stochastic process algebra and model checking. She has led 12 EPSRC funded projects and authored over 70 publications. She is a Fellow of the Royal Society of Edinburgh, the BCS, and the IET.

Dr. Matthew Chalmers – whose research interests include Ubicomp theory, infrastructure and interaction, explored via systems for tourism, health and leisure. His first Ubicomp work was in 1990, using active badges at Xerox EuroPARC. More recently he was a PI in Equator, developing 'seamful design' that exposes infrastructure in interaction. He co-authored the UK Grand Challenge in Ubicomp, and has published in and served on the committees of the Ubicomp, CHI and Pervasive conferences.

Imperial College London – Systems Management and Security Group

The Systems Management and Security group at Imperial College London is a world-renowned group that combines practical work on building tools for the specification and implementation of adaptive systems management and security with more formal approaches to modelling, analysis, refinement and planning. The group's interests span distributed systems, mobile ad-hoc systems and wireless sensing systems. The research is often application-driven and covers a variety of areas including pervasive healthcare, autonomous vehicles and virtual organisations. Current projects include UbiVal - Fundamental Approaches to Validation of Ubiquitous Computing Applications and Infrastructures (WINES), Emanics - European Network of Excellence on the Management of the Internet and Complex Services (EU), CareGrid - Autonomous Trust Domains for Healthcare Applications (EPSRC) and Primma – Privacy Rights Management for Mobile Applications (EPSRC).

Dr Naranker Dulay – is exploring the interplay between security, trust and privacy for context-aware distributed, mobile and pervasive systems. He was an early advocate of architecture description languages and developed the compilers and runtime systems for the Conic and Darwin ADLs developed at Imperial College. More recently he has worked on the Ponder and Ponder2 policy languages and runtime platforms. He is PI on the UbiVal and CareGrid projects above.

Dr Emil Lupu - leads several research projects in the areas of pervasive computing, trust and security and policy-based network and systems management. He has over 60 publications in these areas and serves on the program committee of several international conferences such as NOMS, IM, DSOM, Policy, NSO, SASO, AIMS. Dr. Lupu was program co-chair of the IEEE Enterprise Distributed Object Computing Conference in 2001 and of the IEEE Workshop on Policies for Distributed Systems and Networks in 2001 and 2004.

Professor Morris Sloman is Director of Research and Deputy Head of Department. He leads the Systems Management and Security group. His research interests include autonomic management of ubiquitous and distributed systems, adaptive security management, trust and security for pervasive systems. He chairs the UKCRC Ubiquitous Computing Grand Challenge steering committee, executive panel of the UK Computing Research Committee, and is on the UK Defence Scientific Advisory Council – Information Superiority Board.

Georgia Institute of Technology

The Human-Computer Interaction (HCI) research area, within the School of Interactive Computing (ranked 4th nationally for its Graphics/User Interaction program) at the Georgia Institute of Technology (Georgia Tech) consists of 13 members of tenure-track academic faculty. The HCI group has a 15 year leadership history that can be charted across the course of Human-Computer Interaction research within the United States. Further, the HCI faculty are leaders in the internationally-known Aware Home research program which consists of a residential building designed as a living laboratory for prototyping and exploring next generation networked homes, services, and applications. Results from this research contribute to a variety of fields including Ubiquitous Computing (Ubicomp), Human-Computer Interaction (HCI), and Computer Supported Cooperative Work (CSCW). The HCI research group, leveraging the Aware Home (www.awarehome.gatech.edu) and other resources, is committed to research in the wild—deploying solutions in living laboratories and when possible in people's actual homes. In the design, development, and deployment of solutions, the faculty draw on a broad range of disciplines to ensure that solutions are useable and useful.

Associate Professor W. Keith Edwards – takes an empirically-grounded approach to the design of middleware for user-centred home networking solutions. He has published the results of this research within Ubicomp, HCI, and CSCW. Prior to joining the faculty at Georgia Tech, he was the Manager of the Ubiquitous Computing group at Xerox PARC (a group founded by Mark Weiser), where he led the development of *Speakeasy*, a middleware platform that leveraged mobile code to allow networks to seamlessly discover and utilize new resources. Most recently, he co-authored an ACM Workshop on Hot Topics in Networking (VI) paper that proposes a new network architecture for homes to promote ease of use [Calvert 07].

Associate Professor Rebecca E. Grinter – conducts empirical studies of computing in use in order to understand people's practices and from that derive and influence the design of future technologies. She has published the results of her research within Ubicomp, HCI, and CSCW, and in partnership in Software Engineering, Security and Networking conferences. She led the first studies of end-user difficulties of home networking [Grinter 05] and discovery protocols [Voida 05]. This research continues, and her group have collectively studied 40+ homes across the urban United States empirically examining the lived experience of home networking and networked domestic technologies, including Robotic appliances. Prior to joining the faculty at Georgia Tech, Grinter was a researcher at Xerox PARC and Bell Laboratories.

Industrial Partners

This international academic team is complemented by two key industrial research partners with a strategic research interest in the future of domestic infrastructures. These partners will play an active role in the work of the project dedicating research staff, equipment and access to empirical data to support the work of the project.

Microsoft Research (Cambridge): Will build on existing initiatives at MSR Cambridge in the development of user centred networking approaches for the home involving staff from their networking and Computer-Mediated Living groups as well as providing access to the recently announced Windows Home Server software (see support letter for details).

BT: Involvement from BT will build upon their strategic interest in home networks as one of the leading providers of domestic broadband services. This will include members of their Digital Home Research Programme, their Customers and Markets programme and will link with their current strategies including trials in this area and involvement in the dissemination of this work (see support letter for details).

Part II: Case for Support

Over 300 million people worldwide have broadband connections to the Internet[1] with 51% of UK households having a broadband connection[2]. Many of these households are currently exploring the use of in-home wired and wireless networking, not only to allow multiple computers to share the connection to the Internet, but also to enable media sharing, gaming, and other new applications. However, despite the growing interest in home networking, these technologies remain extraordinarily difficult for people to install, manage, and use. Current approaches provide little support for end-user understanding and control of network technologies and the resulting difficulties are rapidly becoming a key roadblock to the deployment of next-generation applications in communication, healthcare, and entertainment[3]. A recent statement by the Gartner group best sums up the current situation: "*The technical know-how required to set up a network and run music or video across cables or wi-fi, is "the elephant in the room that no-one wants to talk about."* ".[4]

Fundamentally, existing technology-centric models of the infrastructure have no resonance with the understanding employed by users to make sense of their home networks. This proposal builds upon extensive empirical studies charting the mismatch between current networking technology and the needs of the domestic setting undertaken by the applicants in the UK [Tolmie 07; Rodden 07; Crabtree 04; Rodden 04; Crabtree 03] and the US [Shehan 07; Grinter 05; Sung 07; Chetty 07; Shehan-Poole 07] over the last four years. Some scenarios drawn from these studies illustrate the nature of this mismatch.

The surprising consequences of network change

Frank and Sarah wake one Saturday, and come downstairs looking forward to their first cup of coffee, the newspapers and listening to the Today programme on radio 4. To their surprise, no sound emerges from their speakers. The reason is that their neighbours have purchased new Bluetooth-enabled speakers which, when first installed, associate themselves with the nearest sound source; in this case, Frank and Sarah's Bluetooth-enabled stereo. Meanwhile, the neighbours are abruptly awakened to a rather fractious political debate on the decline of research funding in the UK.[5]

Welcome visitors but unwelcome laptops

Steve visits his friends Mike and Elisabeth for the weekend and brings his laptop. Mike has installed a number of wireless access points throughout his home and has secured the network using MAC address filtering. To allow Steve access to the network he will need to get Steve's MAC address, enter this on each of the four wireless points. Steve apologises for the trouble he might cause and rather than be a problem to his hosts suggests he reads his email at a local coffee shop.

Homes are shared but technology is not

Tom and Joan have four teenage children and share a common domestic network. They share a large PC machine which they also use as a media hub for music in the home. They each have their own iPods and are continually frustrated in having to fight against the single iPod per machine assumed by the infrastructure. Tim the teenage son often bemoans the fact that his iPod is "polluted" with his parents' music.

The aesthetics of the home are much more important than the technology

Frank and Linda are a recently married couple. As IT professionals they each have a laptop and a desktop in the home, two digital cameras and a hard disk digital video camera. Becoming concerned about the lack of backups Frank decides to install a network file store. This is initially placed in the living room next to the cable modem and wireless access point. After 2-3 days Linda points out how noisy and ugly the filestore is and insists it be moved to a cupboard alongside the electric meter and other services. In order to do this Frank needs to significantly upgrade his network installing 2 additional access points and a wireless repeater. This takes four weeks to configure.

These are far from unusual scenarios and are indicative of many of the situations emerging from our fieldwork to date. They illustrate how the simplest of domestic activities (*visiting friends*) and decisions (*that machine is ugly can we move this from the living room*?) can have implications for the infrastructure that generate a prohibitive technical overhead. Our empirical studies also indicate that problems with home networking are not superficial, nor will a 'thin veneer' of UI technology layered atop the existing architecture solve them. Rather they are *structural* and emerged from the mismatch between the stable 'end-to-end' nature of the Internet and the dynamic evolving nature of domestic environments.

The Research Challenge

Today's domestic infrastructures are opaque to users and prove clumsy and awkward in day-to-day use. Changing this requires an interdisciplinary partnership between those who design 'end user' technology and interaction, and those who seek to realise future digital infrastructures in order to allow users greater control and ownership of the networks in their homes.

> The challenge is to take a radical approach to future networking in the home by adopting a user centred approach to the creation of the next generation of domestic infrastructure that combines empirical understanding of use with a fundamental re-invention of the protocols, models and architectures of the domestic setting.

This fundamental research challenge stems from the fact that the current suite of Internet protocols and architectures has migrated to the home with little or no reflection upon their appropriateness. The current home network is essentially built around the same protocols, architectures, and tools that were developed for the Internet as a whole in the 1970's. Inherent in the Internet's 'end-to-end' architecture is the notion that the core is simple and stable, providing only a semantically neutral transport service. The Internet was designed for a certain context of use (assuming relatively trustworthy endpoints), made assumptions about its users (skilled network and systems administrators running the edge nodes and network core), and tried to accomplish a set of goals (e.g., scalability to millions of nodes) that are not directly appropriate for the home network.

[1] Internet World Stats see http://www.internetworldstats.com/dsl.htm

[2] Office for National Statistic 28 August 2007 see http://www.statistics.gov.uk/pdfdir/inta0807.pdf

[3] The Consumer Electronics Association (CEA) (http://www.ce.org/) report that home networking equipment is currently the most returned consumer electronics item with return rates for new products in excess of 25%

[4] http://news.bbc.co.uk/2/hi/technology/6949607.stm

[5] This happened to a family in Finland http://gizmodo.com/gadgets/home-entertainment/the-new-way-to-accidentally-spy-on-your-neighbors-007455.php

The assumptions inherent in the Internet actually sit at odds with our understanding of domestic settings. Writers like Stewart Brand [Brand 94] have stressed how our physical environment is subject to continual change with significant implications for the technology in our homes [Rodden 03; Chetty 07]. We routinely reorganise the general "bric a brac" of the home[6], but also periodically repair or replace more inset features such as decor, plumbing, electrics, walls and roofs. As digital devices enter the home we see a similar set of practices. Devices are continuously introduced and removed from home settings, software is routinely downloaded to alter the capabilities of machines, and our friends and family either bring or lend devices to us for various periods of time. Moreover, the porous boundaries of wireless networks mean that we are often impacted by everyday changes that leak from the digital environment of our neighbours.

Now that the Internet has "come home" it is not surprising that widespread problems exist. [Blumenthal 01]. The overhead asked of users in understanding the network and the impact of change is prohibitive. Internet devices, like any edge nodes, need to be configured with link- network- and application-layer settings in order to participate on the network as they are continually introduced and removed from the network as part of the everyday activities of the home. Moreover, the simplicity of the network core also breaks down on the home network, where topology *does* matter as devices are distributed through the home where its physical characteristics need to be overcome via the artful combination of a set of wired and wireless devices each requiring installation, configuration and management.

Simply creating a UI layer for the existing network infrastructure is likely to reify existing problems. Rather, we need to investigate *the creation of entirely new network architectures that reflect the sociotechnical nature of the home by taking into account both human and technical considerations*. We need to explore network architectures that might sacrifice scalability in favour of installability, evolvability, and maintainability. In order to do so we will exploit the local character of the home. Devices tend to be collocated, often accessible by users; they are owned by family and friends and are physically brought to the home. Moreover our activities and actions within the home are open to being sensed and understood. Essentially, the physical setting of the home provides us with a significant source of heuristics that we can understand and offers us a set of everyday well understood practices that might be exploited in managing the infrastructure.

Research Objectives

The realisation of a user-centred digital infrastructure is an ambitious interdisciplinary endeavour and will need to tackle many of the issues identified by the UK grand challenge in Ubiquitous Systems[7]. This proposal brings together researchers with experience in understanding domestic technologies and settings to work closely with researchers who address the engineering and scientific reasoning of the underlying infrastructures. The work will address four key objectives:

- The development and assessment of a range of ***interactive techniques*** that make key features of the domestic infrastructure, including features associated with management, measurement and modelling, available to inhabitants in a way that reflects their needs and allows them to develop sufficiently rich understandings of the supporting system.
- The investigation of new infrastructure ***management approaches*** that significantly reduce the overhead involved in the configuration and management of the infrastructure.
- The development of new approaches to ***infrastructure measurement and monitoring*** that make key information about the supporting infrastructure available to users.
- The elaboration of ***well-founded models*** of the infrastructure that allow reasoning about users' effects on the infrastructure including proving key properties of the infrastructure.

We will undertake our research 'in the wild' in real world settings based on an engagement with UK and US households throughout the duration of the project. These households will provide the sites for rapid prototyping with users, allowing the needs of users from two distinct cultures to shape all aspects of the underlying technology. These real world deployments of emerging technologies will also provide a key point of integration for the project.

Background

Domestic environments have been a source of inspiration for future digital technologies for some time, featuring in Weiser's discussions of ubiquitous computing [Weiser 91] and initiatives such as HP's Cooltown [Kindberg 00]; Philip's Vision of the Future [Philip 95] and MIT's House_N project[MIT 05], among others. A common focus has been the development of Smart Homes [Meyer 03] populated by a set of futuristic devices interconnected by an advanced technical infrastructure. Initiatives such as the Georgia Tech aware home and the deployment of ubiquitous devices "in the wild" within Equator has sought to move from future inspiration to realisation as ubiquitous computing migrates from the research lab into the everyday world. This proposal emerges from previous studies of domestic environments and explorations into the development of user configurable ubiquitous computing installations [Rodden 07, Humble 03]. In addition to highlighting the difficulties posed by existing infrastructures these studies demonstrated the importance of the physical configuration of the home and domestic routines in establishing digital technologies [Crabtree 03]. We wish to exploit these human understandings of the home to guide the management of the supporting infrastructure.

One of our key objectives is to apply user-centred design principles to support users in managing their domestic infrastructure. Management is seen as critical to improving the user experience in domestic settings [Bull 06]. Numerous standards and initiatives seek to simplify home networking. OSGi (www.osgi.org) for example, is an ever-expanding set of APIs for the deployment of services on set-top boxes, cable modems, consumer electronics, PCs, industrial computers, cars, mobile phones, etc. The mission of the OSGi Alliance, however, is to enable service providers like ISPs to deliver revenue-earning services over their networks. Neither OSGi nor other standards directly address the high-level management issues

[6] Indeed, furniture is called "mobilia" in Italian for good reason.

[7] Ubiquitous computing grand challenge - http://www-dse.doc.ic.ac.uk/Projects/UbiNet/GC/index.html

experienced by domestic users. In the research community the most relevant approaches are policy-based management [Bandara 07] and autonomic computing [Dobson 06], but these, to date, have concerned themselves with the needs of large-scale enterprises. The emergence of usability in security and privacy research [Cranor 05] is a welcome exception which we will seek to build upon.

Network measurement plays a key role in management and over the past 20+ years a number *post hoc* measurement capabilities have been designed and developed to support the management of the Internet [Paxson 97]. The advent of the Simple Network Management Protocol (SNMP) [SNMP 90] and the definition of appropriate Management Information Bases (MIBs) for different types of network devices has resulted in commercial acceptance of the need for measurement (each device provides one or more SNMP-accessible MIBs), and commercial network management products (e.g. HP OpenView [Hunt 97]) are now available for managing IP-based networks. The conceptual model of the network for using packages such as OpenView requires that the users have sophisticated knowledge of networking concepts and components at several levels of the ISO network stack. Knowledge of this network-centric conceptual model is increasingly rare in large organizations and is simply unknown in home and SOHO settings. Additionally, the SNMP/MIB approach to network measurement and management is poorly equipped to support efficient management of future networks, whether in the home or the office [FIND 07]. It is clear that such network-centric models for measurement do not map to the understanding employed by users to make sense of their home networks, and the time is ripe for a fundamentally human-centred approach.

Key Research Themes

This project brings together a number of currently disparate research traditions to develop approaches to the domestic infrastructure that enables a much more user-centred approach to its management and use at all levels. Our iterative interdisciplinary research investigation will be structured around four closely related research themes:

- ***User oriented manifestations*** that convey the nature of the infrastructure in terms of its internal architecture, its configuration in the home and that present key features of management, measurement and modelling that will be developed in partnership with household inhabitants. These will allow users to both make sense of the infrastructure and to interact with key elements of it. They will exploit a range of alternative interactive technologies including *personal mobile devices* carried by inhabitants and *shared situated screens* and *physical artefacts* built into the environment.
- ***User driven management approaches*** that allow inhabitants to express their intent to the surrounding digital infrastructure through the expression of policies. Work will explore the development of both *implicit policy setting* based on understanding the sensed actions of users and *explicit policy setting* approaches where the inhabitant directly conveys intent to the infrastructure.
- ***User motivated measurement and monitoring*** will be deployed and will provide one of the key resources to drive the project. This work will focus on dynamic approaches to capturing and describing the nature of the infrastructure based on the establishment of a network measurement plane for the domestic network that will capture information and statistics of use to inhabitants and external experts.
- ***User focused computational models*** of the infrastructure will be elaborated that allow reasoning about key features of the infrastructure (e.g. the extent to which they are preserved), exploration of the consequences of users' actions and the relationship to their intentions, and presentation of models of user behaviour and infrastructure to the people modelled.

These closely linked themes will allow us to exploit highly iterative prototype development in the home to inform longer term infrastructure construction and overall formal modelling approaches.

User Oriented Manifestations

The driving consideration for the project will be how the infrastructure is actually manifest to and understood by users. A "seamful design" approach will be exploited to selectively and deliberately expose infrastructure features drawn from the other themes to inhabitants in novel and useful ways. The work within this theme will combine *empirical understandings* of how users currently make sense of and manage their domestic infrastructures to allow us to identify new ways to reveal and use infrastructure features. The *rapid prototyping* of novel alternative manifestations will directly inform our work on modelling, infrastructure configuration, management, measurement and monitoring.

Empirical understandings will focus on understanding the ways in which home networks are currently understood and managed. Initial investigations will build upon our existing ethnographic studies of domestic settings (e.g, [Tolmie 07; Crabtree 04; Rodden 04, Crabtree 03; Shehan 07; Grinter 05; Sung 07; Chetty 07]). We will use lightweight 'technology tours' and semi-structured interviews as a means of initial engagement with the users. These will be used to drive a series of co-design workshops where we will articulate with users a series of potential prototypes. A selection will be later deployed as 'technology probes' subject to formative assessment to reshape the nature of the infrastructure manifestation and to refine the measurement and management approaches. Empirical investigation of these prototypes will exploit *record and replay facilities* emerging from Equator [Crabtree 06, Morrison 07] and currently released[8] through the National Centre for eSocial Science to combine recording of the physical setting with information captured from the digital infrastructure.

Rapid prototyping will exploit a range of technologies to present the network to inhabitants using two complementary strategies, *centralised manifestations* where network information is focused on a small number of situated displays within the home and *distributed manifestations* that exploit mobile devices to deliver network manifestations to users as they move through their homes and when away from their homes. Initial prototypes will focus on 'mock ups' to explore the sorts of information required to understand the network and the paradigms and approaches that make most sense. These will help shape underlying infrastructure capabilities in measurement, management and modelling. Later versions will be realised using a

[8] http://www.mrl.nott.ac.uk/research/projects/dress/software/DRS/Home.html and and http://www.dcs.gla.ac.uk/~matthew/DCS/Replayer.html

combination of commodity devices (for example the Nokia N800) and specially constructed and designed devices (exploiting systems such as phidgets or gumsticks). The cost of these prototypes will be reduced through the use of Equip, an open source rapid development platform for ubiquitous computing (available at http://equip.sourceforge.net).
A series of regular ***project wide debriefing workshops*** will be held to convey the emerging results of empirical studies and the formative assessment of user experiences of prototype manifestations to the other themes

User Driven Management Approaches

Our user centred approach will inform the realisation of a management and security infrastructure that is proactive, selectively visible and secure; where users can focus on high-level policies and have management functions explained to them.
User-centred Policies will draw upon the needs of domestic users to express *explicit management and security policies* as well as exploring *implicit policies*. Our initial emphasis will be on management of *access, privacy and security*. In conjunction with the manifestations theme we will develop prototypes that map user expressed desires into enforceable policies, perform analysis and provide feedback. Work will also explore the potential for implicit policies learned from repeated user actions and routine practices. The key challenge will be to develop a policy approach that can be used to reason about all of these policies, user-elicited, inferred and learned policies and device-based policies whilst also being comprehensible to domestic users. The Ponder2 policy language (www.ponder2.org) and analysis tools [Bandara 07] will be used as a starting point.
User-centred Self-Management will focus on developing a proactive approach to domestic network management where each active device takes responsibility for managing itself and coordinating with other devices to maintain the high-level policies. The challenge is to develop techniques and tools that inform users of the implications of network changes in terms that they readily understand and can respond to. In conjunction with the Measurement and Monitoring theme we will develop an infrastructure that can configure and repair itself and investigate when and how to inform and involve users in repair tasks. For the latter, we will explore with users the most appropriate ways to involve them in management tasks, for example troubleshooting loss of wireless connectivity. The self-managed cell architecture [Lupu 07] developed by Imperial and Glasgow will be used as a starting point. We will draw upon the Manifestion and Modelling theme to extend this with models for domestic networks, physical and personal spaces, home users and devices informed from real world settings.

User Motivated Measurement and Monitoring

Our user-centred manifestations and management approaches require us to reconsider network measurement & monitoring to reflect the ways home users make sense of their networks.
Domestic Measurement Techniques will move beyond existing MIB approaches to develop an approach that exploits the local character of the domestic setting with an emphasis on the characteristics of network flows. Measurements of these characteristics are traditionally done in two different ways: *passive measurements*, in which a component measures characteristics as the packets fly by, or *active measurements*, in which synthetic traffic is injected into the network and the characteristics of the injected traffic are measured. Passive measurements are restricted to characteristics of flows that can be measured at a single point, while active approaches can perform 2-point measurements providing accurate measurements of additional characteristics such as packet delay and jitter; these 2-point measurements are important in converged network settings. However, as today's network is quite sophisticated at associating different qualities of service to different flows based upon packet header fields; one cannot guarantee that the synthetic flows will be treated exactly as the real flows. Recent work on inline measurements [Pezaros 04] has shown that it is possible to actively carry out the necessary 2-point measurements and eliminate inference errors by tagging actual traffic with measurement data using IPv6 extension headers. In this project, we will use a variant of this technique (but for IPv4) to generate the requisite measurement data required to support human-centred management principles.
Deriving a Domestic Measurement Plane will explore the utility of a domestic measurement plane. As the networking community investigates the next generation Internet, it has become increasingly obvious that a *knowledge/measurement plane* [Clark 03] that complements existing data and signalling planes is required. This 3rd plane can be likened to a distributed database, where some of the content is raw data while other content is derived. For example, the Sophia system [Wawrzoniak 04] provides an "information plane" for PlanetLab based upon a distributed system that collects, stores, propagates, aggregates, and reacts to observations about the network's current conditions. Through the provision of this distributed database, and sophisticated mechanisms for accessing the information, it is possible to provide a richer set of information about the workings of the network to support management, in general, and human-centred management, in particular. Work in the DIAS project [Galpin 08] has involved the creation of an extended stream query language for defining the required aggregation of measurements pushed from network components in a way that optimizes the amount of information transferred. Within this theme we will exploit the lessons from the Manifestations and Management themes to realise a measurement plane suitable for the domestic environment. A primary requirement for the measurement system is that it also be able to accumulate measurement data for the activity within the home network so as to enable 3rd-party involvement in network support. Through the provision of a richer set of measurement data using inline measurement techniques, and the integration of these data sets into a Sophia-like distributed information plane, we will provide the required input to support user-centred management, the design of user oriented manifestations and such 3rd-party network support.

User Focused Computational Models

This project offers a unique opportunity to model and analyse in tandem with both design and user experience. One objective is to show the contribution (or otherwise) of computational modelling to meeting the special demands of policy models and user-centred design. Computational modelling will be used iteratively and interactively, to pose and evaluate the key question: is the proposed infrastructure fit for purpose? Formal computational models are ideally suited to this task because they are good for articulating context, default assumptions, temporal, uncertain and stochastic behaviour. These are all crucial aspects of highly concurrent, dynamic, user centred systems. The underlying models will be Kripke structures (for non-stochastic

aspects), Markov chains (discrete or real time), and Markov decision processes for stochastic aspects. Properties will be expressed using appropriate logics (e.g. PCTL, CSL) and checked with model checkers such as PRISM [Kwiatkowska 02] or SPIN [Holzmann 03]. There is a strong link to the research on (user-centred) policy management through the common underlying concept of features, and new techniques will include extending Calder's previous work on offline and runtime feature interactions [Calder 06, Calder 03]. Another novel aspect of the work will be seamfully exposing models of infrastructure and user behaviour to those modelled, via end-user manifestations that present to users selected outputs from model checkers running in the home. In these ways, the computational models theme will interact with the themes that deal with users' own understanding and articulation of needs, norms and fitness for purpose.

The Programme of Work

We adopt a user centred approach to co-develop an infrastructure in close cooperation with our householders that supports their needs. To initiate this approach we will exploit our baseline of existing fieldwork and computing infrastructures to develop an *initial pre-prototype*. An iterative approach will then be adopted where ***'in-situ' user centred prototyping*** of the infrastructure manifestations will be complemented by ***'in depth' refinement*** of the underlying measurement, management and modelling approaches. These prototyping and refinement phases will be complemented by broad assessment and replanning allowing the project to reflect on deeper lessons before assembling the next generation of infrastructure and manifestations to be placed in domestic settings. The broad approach is illustrated in Figure 1 below.

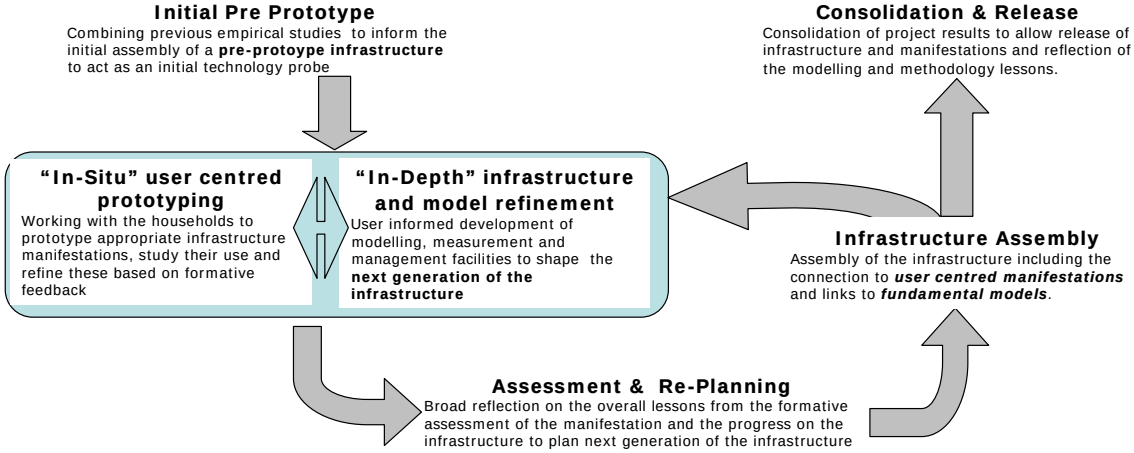

Figure 1: Our iterative approach to shaping a user centred infrastructure

The workplan has five distinctive phases, with workpackages reflecting the project's key themes. The phases, workpackages and partner contributions are summarised below. These should be read in conjunction with the workplan diagram in part III.

PHASE 1 SHAPING A COMMON APPROACH (MONTHS 1-3)
This initial phase of the project focuses on migration of our existing empirical studies, platforms and technologies with the production of a common vision document, seed infrastructure and prototyping schedule.

- ***WP 1.1 Recruitment and prototype preparation*** (*Nottingham (Co-ord), Georgia Tech, Glasgow*) will establish long term links with the households who will provide the core sites for the project. Our aim is to recruit 5 UK households for phase II; these will be complemented by 5 US households during phase III with a plan to grow to 20 households for the final phase of the project. Recruitment will be complemented by prototype preparation. An initial set of technological probes will be outlined that build upon the results of existing studies and exploit the initial pre-prototyping framework.
- ***WP 1.2 Seed platform*** (*Imperial (Co-ord), Glasgow, Nottingham*) will assemble an initial skeleton platform to support prototyping work in Phase II. This will involve the importation and consolidation of existing platform work at Nottingham (Equip) with work at Imperial (Ponder2) and Glasgow (Domino, inline measurements). The output from this work will be a seed architecture and measurement approach to feed into the management (2.3), measurement (2.4) and modelling (2.5) work in phase II

PHASE I1 UNDERSTANDING REQUIREMENTS AND CO-DEVELOPMENT WITH USERS (MONTHS 3-15)
Emphasis during this phase will be on understanding the nature of the domestic infrastructure from the perspective of the inhabitants with emerging results transferred through a series of *focused design workshops* involving all members of the project and members of the project households.

- ***WP 2.1 Empirical Studies*** (*Nottingham (Co-ord), Georgia Tech, Glasgow*) will focus on undertaking empirical studies of the existing practices of the home network. These studies will build upon the seed platform provided from the initial phase with a view to informing the measurement and management approaches to be developed in this phase. The work will exploit the Digital Replay System (DRS) [Crabtree 06] and Replayer [Morrison 07] tools to produce an interactive digital record of these households linking human activity in the home with underlying infrastructure effects.
- ***WP 2.2 Prototyping Initial Manifestations*** (*Nottingham (Co-ord), Georgia Tech, Glasgow*) will be developed in partnership with users through a series of in-situ prototyping sessions. These sessions will focus on uncovering representations of the infrastructures that make sense to household members and the elaboration of appropriate management and modelling

strategies. This will also explore the extent to which the physical environment and the ability to sense human activities in this environment can be exploited as a resource to inform strategies in the underlying infrastructure.

- ***WP 2.3 Management*** (*Imperial (Co-ord), Glasgow, Nottingham*) will identify and model users perceptions of concepts such as roles and relationships, physical and personal boundaries, ownership, privacy and security. These will be mapped into underlying formalisms and policies amenable to reasoning and implementation. An initial prototype will also be developed to elicit requirements and provide feedback to users.
- ***WP 2.4 Measurement*** (*Glasgow (Co-ord), Imperial, Nottingham*) will compare/contrast Sophia and DIAS approaches to the distributed database aspects of the knowledge plane; the final design for the system will be specified, and an initial prototype constructed. An IP-in-IP encapsulation version of inline measurements will be implemented in a Linux-based wireless router and a Linux-based laptop. Baseline measurements will be implemented and accessed via this system.
- ***WP 2.5 Modelling*** *(Glasgow (Co-ord), Imperial, Nottingham)* will concentrate on deriving appropriate abstractions, for example teasing out the crucial nondeterministic or probabilistic aspects. We will concentrate on proving generic safety properties such as freedom from deadlock, for different assumptions and distributions of user behaviour, and on proving integrity of policies.

A project wide ***assessment and re-planning*** (2.6) activity will inform the strategies to be adopted in the following project phase and a ***assembly work package*** (2.7) involving all project members will combine the developed infrastructure and manifestations for deployment and use in phase III.

PHASE II1 EVOLVING A USER CENTRED INFRASTRUCTURE (MONTHS 15-27)

The focus here will be on evolving the initial infrastructure with a particular emphasis on how this supports the ***control and management of the domestic network***.

- **WP 3.1 Empirical Studies** (*Nottingham (Co-ord), Georgia Tech, Glasgow*) will focus on formative studies of the deployed framework to emerge from phase II to understand how these are used in practice to control issues of access, security and privacy in the domestic setting. Our aim will be to uncover user oriented approaches to expressing policy in this domain.
- **WP 3.2 Refining Initial Manifestations** *(Nottingham (Co-ord), Georgia Tech, Glasgow)* will investigate interactive facilities to support users' control and awareness of the infrastructure. As before, prototyping will be undertaken within domestic settings in close cooperation with users to explore control, management and awareness approaches that exploit the physical proximity of technology in the home using a combination of distributed and centralised device arrangements.
- **WP 3.3 Management** *(Imperial (Co-ord), Glasgow, Nottingham)* will develop approaches to validate the operation of a basic policy infrastructure with analysis, enforcement and explanation of user-elicited and lower-level system policies. Validation will be done primarily through testing but also with respect to user requirements and conducting user-studies. Prototypes of the infrastructure will be deployed in homes and incrementally refined based on user feedback.
- **WP 3.4 Measurement** (Glasgow (Co-ord), Imperial, Nottingham) will augment the implementations of the knowledge plane and inline measurement capability based upon initial feedback and more advanced aspects of the architecture of each. The implementations will be extended to Windows-based systems, both laptops and media centres. Input from WP 3.3 will drive the implementation of additional measurements conducted in this environment. The augmented prototype will be deployed in homes and incrementally refined based on user feedback.
- **WP 3.5 Modelling (**Glasgow (Co-ord), Imperial, Nottingham) will develop enhanced models (mirroring the enhanced architecture), prove policy based and domain specific properties, and develop initial abstractions suitable for end user manifestations. Many of these will be derived from use scenarios inspired by the user centred prototyping sessions.

Again, this phase will be concluded with a project wide ***assessment and re-planning*** (3.6) and ***assembly work package*** (3.7) involving all project members to combine the developed infrastructure techniques and the infrastructure manifestations ready for deployment in phase IV.

PHASE IV MANIFESTATION AND INFRASTRUCTURE REFINEMENT (MONTHS 27-39)

The penultimate phase will emphasise how we might reach ***beyond the boundary of the home*** to allow remote 3rd party involvement and aggregate reasoning across a number of homes.

- ***WP 4.1 Studies of the refined manifestations*** (*Nottingham (Co-ord), Georgia Tech, Glasgow*) will explore how the refined infrastructure and manifestations may be used by a number of households. A particular focus will be on how those outside the household are provided access to manifestations and information on the policies and status of the network. We will be particularly interested in how these support remote help from and negotiation with third parties.
- ***WP 4.2 Extending the Manifestations*** (*Nottingham (Co-ord), Georgia Tech, Glasgow*) will further refine the manifestations developed as part of the previous assembly. Our focus will broaden to include remote access and availability through these manifestations, the specification of appropriate policy techniques to remotely manage the infrastructure, and means for those in the household to manage how they are thus presented to third parties.
- ***WP 4.3 Management*** (*Imperial (Co-ord), Glasgow, Nottingham*) will extend the basic policy infrastructure to support remote management, workflow-based management and learned policies. As before prototypes will be developed in homes and incrementally refined based on user feedback.
- ***WP 4.4 Measurement*** (*Glasgow (Co-ord), Imperial, Nottingham*) will extend the knowledge plane and inline measurement capability implementations to address any remaining architectural features. The implementations will also be extended to Windows-based PDAs, and possibly other, more constrained, computing components. At this stage we will also test the systems when there are several active networking components in the home; up to now, we have restricted ourselves to a single wireless router surrounded by one or more clients/servers. The prototypes will be incrementally refined based on user feedback.

- ***WP 4.5 Modelling*** (*Glasgow (Co-ord), Imperial, Nottingham*) will extend models and reasoning, in line with the refinements, concentrating especially on learned policies, and establishing a feedback loop between models and user behaviour—mediated by the manifestations of 4.2—that afford integrity of infrastructure, intervention by third parties, and the confidence of users.

This phase will be concluded with a project wide ***assessment*** (4.6) and assembly ***work package*** (4.7) to shape the final infrastructure and manifestations for consolidation and release.

PHASE V: CONSOLIDATION AND RELEASE (MONTHS 39-42)

This concluding phase of the project focuses on consolidation and release of the results of the project. Software and infrastructure results will be made available in the public domain through a ***final release workpackage*** (5.1). This will be complemented by a ***grand challenge consolidation workpackage*** (5.2) which will consolidate the conceptual results of the project and document the contribution as a foothill project for the Grand challenge in computing. This will involve the publication of summative research papers in leading journals.

Project Management

The project will build upon extensive experience across the consortium in multi-site interdisciplinary research projects. The project will be coordinated by Tom Rodden at Nottingham as part of his Senior Fellowship activities and will build upon the experience of the MRL. **A management group** will be responsible for the ongoing management of the grant and will consist of representatives from each site. This will meet formally four times a year to review progress. These meetings will be supplemented by regular telephone and video conferencing sessions. The management group will draw upon the experience of Dr Hazel Glover, who was the administrator for Equator, in her role as director of operations for the Mixed Reality Lab. The project will be also be supported by a dedicated **electronic environment.** A BSCW online repository will enable project staff and external collaborators to share plans, papers, data and video material as part of work of the project. This will be supplemented with audio/video conferencing.

Relevance to Beneficiaries

Researchers: Ubiquitous computing has emerged as a key UK research strength through initiatives such as the WINES initiative and the Equator IRC. Part of this interest has been within the domestic arena and our emphasis on the domestic infrastructure will provide the foundation for future work in this space. Moreover, the lessons gained in user centred infrastructures will contribute directly to the UK Grand Challenges and inform future work on Ubiquitous Computing Environments. The work will also represent a significant interdisciplinary exploration of these issues, and the methods and techniques used will be of benefit to future researchers. Research results will be targeted to key venues to engage with the key communities involved.

Industrial and commercial groupings interested in the rapidly growing area of the home will benefit. In addition to providing new management and measurement techniques the work will also provide significant understanding of the nature of the home of direct relevance to the growing number of commercial concerns targeting the home. We also believe the approach we adopt could be truly disruptive in this area creating new market opportunities for the UK.

The general public will gain user centred techniques and approaches to the management of technologies for the home. This will allow services for assistive living, healthcare monitoring and leisure to more readily find a stable place in the home.

Dissemination and Exploitation

The groups are well-established and well-connected and industrial, commercial and academic contacts will be used to disseminate the results of the proposed research as well as a variety of research venues. Free access to any systems will be given to academic institutions and a publicly accessible web site will be maintained for the dissemination of results. We intend to make any software artefacts and device designs available via open source distribution. We will build upon our existing public dissemination work to emphasise issues of ethics and societal impact as a key feature of this work.

The long term and transformative position adopted by this proposal also offers significant potential industrial benefit. Current US based home network market leaders (Netgear, Linksys, Buffalo, D-Link) have taken a commodity approach, often reselling the same home router hardware platform built by Broadcom. Their differentiation is limited to box style and quality of documentation. Our approach is potentially disruptive in this space, and can provide an opportunity for new businesses to differentiate themselves over competitors by providing compelling solutions to address the problems of networking in the home. These solutions could be marketed to consumers directly, or to ISPs or other service providers, who currently take the brunt of support and troubleshooting calls for consumers and would thus be motivated to adopt solutions that mitigate these costs. In addition to exploring the appropriate routes to these future markets with our industrial partners BT and MSR, we will actively explore the possibility for spin-outs from this project in collaboration with our university innovation services.

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