EPSRC
Engineering and Physical Sciences
Research Council

EPSRC
Polaris House, North Star Avenue, Swindon, Wiltshire,
United Kingdom SN2 1ET
Telephone +44 (0) 1793 444000
Web http://www.epsrc.ac.uk/

First Grant - Revised 2009
PROPOSAL

Document Status: In Approver Pool
EPSRC Reference:

Computer Science

Organisation where the Grant would be held

Organisation	University of Nottingham	Research Organisation Reference:	23070
Division or Department	School of Computer Science		

Project Title [up to 150 chars]

Xendroid: Cloud-hosting Your Mobile Devices

Start Date and Duration

a. Proposed start date	01 January 2012	b. Duration of the grant (months)	15

Applicants

Role	Name	Organisation	Division or Department	How many hours a week will the investigator work on the project?
Principal Investigator	Dr Richard Mortier	University of Nottingham	School of Computer Science	4

Objectives

List the main objectives of the proposed research in order of priority [up to 4000 chars]

The objectives of this project in priority order are:

1. High quality publications disseminating results from increased understanding of the possibilities latent in the combination of ubiquitous mobile devices and cloud computing, concretely realised through working prototype systems.

2. Public release of code implementing a working system supporting transparent execution in the cloud of code written for mobile devices, and providing containment of private data.

3. Generation of sufficient expertise and momentum in this area in the host institution to apply successfully for follow-on funding in order to grow this area within my host institution.

Summary

Describe the proposed research in simple terms in a way that could be publicised to a general audience [up to 4000 chars]. Note that this summary will be automatically published on EPSRC's website in the event that a grant is awarded.

We are seeing unprecedented availability of public computing via the ability to rent computers in "the cloud" to perform whatever computing task is desired. This is enabled using the technology known as "virtualisation" which transparently and flexibly partitions a computer's hardware for simultaneous use by multiple operating systems. This gives great flexibility in computing resource: you no longer have to make large up-front capital investment to use the latest computing hardware. Instead you simply rent a virtual machine for the hours, days or months you require, installing software on it as if it were your own entire server.

At the same time, mobile devices are becoming ever smarter and more widespread. In many cases the phone in your pocket is as, if not more, powerful as your desktop computer was just 10-15 years ago. This trend is accelerating and widespread, with developing nations in, e.g., Africa forgoing wired telecommunications infrastructure for wireless. This rapid expansion comes with a set of problems including fragmentation in the market as new devices become available on ever shorter timescales, as well as further increasing the gap between the technology available to developing nations and that in the industrialised west.

In this context, the vision of this research is to apply the technique of virtualisation to use the plentiful computing resources in the cloud to transparently support the latest mobile software on a variety of existing and legacy devices. This involves understanding how best to design and implement protocols and software that will make it possible to run software in the cloud while appearing to run it on the mobile device. A particular challenge in doing this arises because mobile devices often contain a great deal of very sensitive personal data, as well as provide a rich set of sensors that can easily reveal personal data -- consider, for example, the recent discoveries of location tracking in both iPhone and Android smartphones. Containing and controlling this personal data so as to avoid infringing users' privacy is a key requirement.

If successful, this project will produce a range of benefits, e.g., people will effectively be able to upgrade performance of their phones without needing to replace the hardware; people will be able to use software written for incompatible devices, breaking down some of the walls that app providers impose; and it might even help to reduce the growing gap in technology availability between the industrialised west and the developing world, by enabling the latest smartphone software to be accessed by less capable legacy devices as are common in the developing world.

Academic Beneficiaries

Describe who will benefit from the research [up to 4000 chars].

Academic beneficiaries obviously include the systems/networking community, both nationally and globally, through the usual dissemination of results. Additional benefit will arise through release under suitable open source licenses of working code, enabling other researchers to build directly on work done in this project. Specific elements of understanding that will be generated include how best to design protocols for such a mixed mobile/cloud environment, as well as how to instrument and analyse performance in such environments.

Within the UK, and with the support of my host institution, this project also represents the first steps in building a new systems and networking research group. Although of high quality, the existing UK community in this field is relatively small; its expansion to include the University of Nottingham will strengthen the UK's ability to compete with the rest of the world, notably the USA, in this important field.

Outside the computer science field, this project will produce a platform and the opportunity for study for the business/innovation research communities. The potential impact of a platform such as Xendroid is substantial, affecting mobile operators, handset vendors, software vendors, and software developers. The removal of the walls created by, for example, different mobile application platforms could significantly alter the business landscape in terms of platform ecologies and value chains. To begin to study this, the interdisciplinary Horizon Digital Economy Research Institute is willing to contribute 6 months of business/innovation researcher time.

Finally, there is similar potential for cross-pollination between existing projects at the University of Nottingham, notably the recently successful Bridging the Urban Divide (BURD) bid "Scaling the Rural Enterprise" involving both Nottingham and Horizon, funded by the RCUK and the Indian DST. Within that BURD project, mobile technologies are being used to help rural communities in the UK and India to scale up their production through better coordination and control of the supply chain. By enriching the capabilities of mobile devices, and by making available cloud computing resources in situations where they are not currently easily accessed, the Xendroid could help extend the capabilities available within the BURD project.

Impact Summary

Impact Summary (please refer to the help for guidance on what to consider when completing this section) [up to 4000 chars]

In addition to the academic beneficiaries already discussed, this research will have public and commercial beneficiaries. Commercial beneficiaries will include industrial researchers and software developers, particularly the large number of "cottage industry" developers that currently supply many mobile smartphone applications on the Android and iPhone/iPad platforms. By providing means to allow users to experience software for one platform on devices from the other, these developers will immediately gain access to larger markets for their products.

Users will benefit from the ability to access a wider range of applications from their mobile devices, including applications that are not possible, or simply not available, to run on their devices. Other potential user benefits include the ability to logically coalesce multiple devices into one by providing e.g., a work mobile device as a cloud hosted image accessed via the user's personal mobile device while the employer maintains complete segregation and control over sensitive business assets.

The software outputs of this project may bring direct benefit to commercial developers, in both large companies and small startups. Indeed, if the opportunity presents itself, it might be possible to spin out commercial development of this project's outputs directly, following the model pursued by e.g., the University of Cambridge with XenSource and the open source Xen virtualisation platform. Engagement with the core Xen team at Citrix provides a channel for any software or design impact on the Xen platform itself.

Summary of Resources Required for Project

Financial resources

Summary fund heading	Fund heading	Full economic Cost	EPSRC contribution	% EPSRC contribution
Directly Incurred	Staff	49813.00	39850.40	80
	Travel & Subsistence	3417.00	2733.60	80
	Other Costs	5553.00	4442.40	80
	Sub-total	**58783.00**	**47026.40**	
Directly Allocated	Investigators	7212.67	5770.14	80
	Estates Costs	7312.00	5849.60	80
	Other Directly Allocated	174.00	139.20	80
	Sub-total	**14698.67**	**11758.94**	
Indirect Costs	Indirect Costs	51512.00	41209.60	80
	Total	**124993.67**	**99994.94**	

Summary of staff effort requested

	Months
Investigator	1.5
Researcher	15
Technician	0
Other	0
Visiting Researcher	0
Student	0
Total	16.5

Other Support

Details of support sought or received from any other source for this or other research in the same field.

Other support is not relevant to this application.

Staff

Directly Incurred Posts

			EFFORT ON PROJECT							
Role	**Name /Post Identifier**	**Start Date**	**Period on Project (months)**	**% of Full Time**	**Scale**	**Increment Date**	**Basic Starting Salary**	**London Allowance (£)**	**Super-annuation and NI (£)**	**Total cost on grant (£)**
Researcher	Research Fellow	01/01/2012	15	100	N/A	01/08/2012	31798	0	7520	49813
									Total	49813

Applicants

Role	Name	Post will outlast project (Y/N)	Contracted working week as a % of full time work	Total number of hours to be **charged** to the grant over the duration of the grant	Average number of hours per week **charged** to the grant	Rate of Salary pool/banding	Cost estimate
Principal Investigator	Dr Richard Mortier	Y	11	220	4	54095	7213
						Total	7213

Travel and Subsistence

Destination and purpose		Total £
Within UK	Dissemination - conference registration - 2 UK conferences	400
Within UK	Dissemination - UK travel to conferences - 2 return trips	300
Within UK	Dissemination - subsistence for 2 UK conferences - 4 days total	160
Outside UK	Dissemination - conference registration - 1 international conference	417
Outside UK	Dissemination - travel - 1 international conference	800
Outside UK	Dissemination - subsistence for international conference - 6 days	300
Within UK	Dissemination - accommodation - UK conferences	320
Outside UK	Dissemination - accommodation - international conferences	720
	Total £	3417

Other Directly Incurred Costs

Description	Total £
Airtime for mobile phones and tablets	875
Android phone	300
iPad - 3G and WiFi	579
iPhone 4	510
Non-smart (legacy feature) phone	100
iPhone software development kit	65
Cloud-hosting funds - Github and Amazon EC2	1025
High-spec laptop - Apple Mac laptop	1500
HTC Flyer tablet - Android	599
Total £	5553

Other Directly Allocated Costs

Description	Total £
Infrastructure Technicians	174
Total £	174

Project Partners: details of partners in the project and their contributions to the research. These contributions are in addition to resources identified above.

1	Name of partner organisation	Division or Department		Name of contact	
HORIZON Digital Economy Research		Computer Science		Professor Derek McAuley	
Direct contribution to project			**Indirect contribution to project**		
	Description	**Value £**		**Description**	**Value £**
cash			use of facilities/ equipment		
equipment/materials			staff time	6 months RA time; access to business development team	32000
secondment of staff			other		
other			Sub-Total		32000
Sub-Total		0		Total Contribution	32000

Total Contribution from all Project partners: £32000

OTHER INFORMATION

Reviewers

1	Name	Organisation	Division or Department	Email Address
Professor Saleem Bhatti		University of St Andrews	Computer Science	saleem@cs.st-andrews.ac.uk

Reviewers

2	Name	Organisation	Division or Department	Email Address
Professor Nigel Davies		Lancaster University	Computing & Communications	nigel@comp.lancs.ac.uk

Reviewers

3	Name	Organisation	Division or Department	Email Address
Professor J Smith		University of Pennsylvania	UNLISTED	jms@cis.upenn.edu

Impact Audience	**Targeted Benefit**	**Transfer Mechanisms & Timescale**
Academic community	Knowledge transfer	Access to code artefacts and publication in suitable venues of key results, including but not limited to: • novel protocol design and evaluation; • system architecture and performance; • multi-resource scheduling algorithms. (*First submission after 4 months, and then throughout*)
UK computer science research community	Increased strength in systems and networking	Training and development of a PDRA in systems and networking methods and techniques. This forms progress towards one of the School of Computer Science's long-term goals, to build a strong systems and networking research group, in line with the broader University of Nottingham research strategy. (*Project lifetime and beyond*)
Developer community	New development and deployment opportunities. Opening up of new markets.	Public availability of code under open source licenses. (*Throughout project*)
General public	Deployment of developed platform	Make contact with and follow up results with industrial partners via Horizon Digital Economy Research Institute. (*Regular interactions with Horizon and subsequently contacted partners during project*)
UK plc	Reduced cost, increased demand	Businesses will benefit by reduced IT costs by being able to utilise and manage sensitive data on employees personal devices. Xendroid will also serve to drive increased demand for licensing of UK-based ARM's intellectual property to build low-power servers to provide improved performance of native ARM Android code. (*Interactions with partner during project*)
Developing world	Increased inclusivity	Public availability of code. Use of platform by, e.g., BURD research project. This will help increase availability of state-of-the-art smartphone capabilities and development platforms to those in the developing world, enabling them to develop software with greater export value. In conjunction with above, deployment by industrial partners. (*End of project*)

horizon
DIGITAL ECONOMY RESEARCH

Horizon
University of Nottingham Innovation Park
Triumph Road
Nottingham
NG7 2TU

23rd May 2011

Dr. Richard Mortier
School of Computer Science
University of Nottingham

Re: Cloud-Hosting Your Mobile Devices

Dear Richard,

Horizon is a Research Institute at the University of Nottingham engaged in Digital Economy Research. Initial funding of £20m was obtained through the RCUK Digital Economy Hub and DTC programmes; this funding includes research activity in collaboration with “spokes” at the Universities of Brunel, Cambridge, Exeter and Reading. Our research concerns the human, innovation and technical challenges of ubiquitous computing in the Digital Economy.

Your proposed work on cloud-hosting mobile devices complements the existing Horizon technical work-plan and we have been delighted to discuss and help you refine your ideas around this topic; we would also welcome the opportunity to both challenge the design and build on your developments in specific “research in the wild” deployments once an initial prototype is available.

Two technological trends in the last few years have had a radical impact on the provision of services to consumers – the adoption of virtual machine technology to build cloud computing centres and the penetration of the smart phone as the point of delivery for many of these new services. These have already had a transformational effect on the mobile phone industry: equipment suppliers, service operators and software vendors are all undergoing significant structural change. Further combinations of these technologies, such as those you suggest, will have further major impacts and as part of the Horizon support to your technical work programme, we will support 6 months of a business research associate to investigate these innovation related commercial issues.

Horizon has an extensive network of industrial partners and we would welcome the opportunity to feature your technology in our broad partner engagement and will make available our business development team to help you forge new links. In this regard I think the innovation related work will be most informative in directing our outreach as it is currently unclear which sectors will be the winners and losers!

We estimate that the contribution of RA time and BDE amounts to an equivalent of £32000 in Horizon support for your project.

Yours,

Professor Derek McAuley
Director of Horizon

The University of Nottingham

Vision. Ongoing development in mobile device capabilities looks set to continue changing the world. Unfortunately, we see fragmentation of both platforms and use arising at the very point they are becoming the key means for people to manage their digital lives. The former because each vendor wants exclusive ownership of such a growth market leading to incompatible offerings, e.g., Apple's App Store, or Google and Amazon's Android Marketplaces. The latter due to the need for people to maintain different digital contexts, e.g., the desire of employees to own and control their own device while their employer also desires them to carry and use a work-specific device.

A possible resolution to these problems of fragmentation comes from the IT industry, which has been revolutionised in recent years by the application of virtualization. This has led to dramatic shifts in cost structure and the rise of cloud computing, making high-power data-centre facilities available to the public. The vision of this project is to apply virtualization to the fragmenting mobile smart-device market, benefitting users through improved performance and easier management of devices, and the opening up new possibilities for cross-over between devices. Figure 1 depicts *Xendroid*, the key platform output of this research, enabling Android images to be hosted in the cloud and accessed from featurephones, iPhones/iPads and other Android devices.

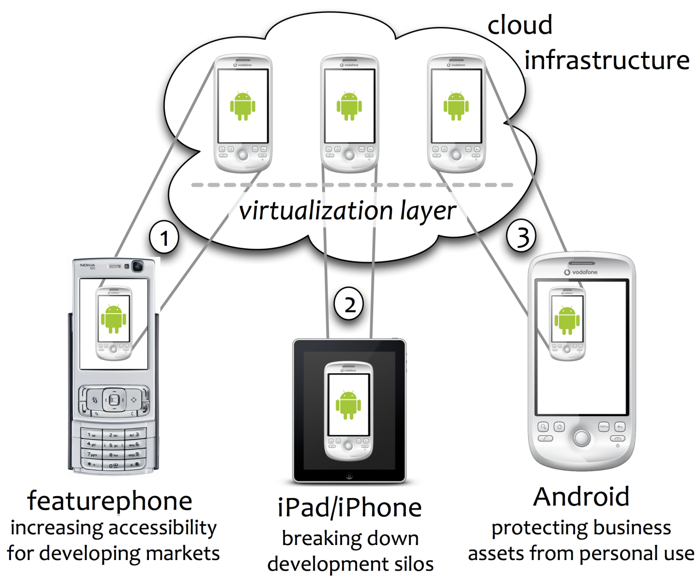


Figure 1: Overview of *Xendroid*.

Research Hypotheses & Objectives. Successfully realising this vision is more than a simple matter of programming. The context in which any solution must operate is complex, matching the resource demands and capabilities of increasingly capable *sensor-rich* but still *mobile* devices, high powered *cloud computing* facilities, all while respecting the *privacy constraints* of people and businesses. We pose three specific research challenges:

(*i*) How should we design and build scalable protocols to best support leveraging of the cloud by the wide range of mobile handheld devices, from relatively dumb featurephones to the latest smartphones?

(*ii*) What measurement infrastructure is required to enable optimal scheduling of execution between the device and the cloud based on relevant parameters (battery life, execution time, monetary cost)?

(*iii*) How should we make personal device sensor data (e.g., images, audio, video, location) available to cloud-hosted applications efficiently and in a context-aware manner?

The design space of possible approaches is broad, ranging from "remote desktop" style interaction using either simple image blitting (cf. VNC [1], RDP[1]) or higher-level graphics primitives (e.g., the X Window System [2]); to application-level code mobility (e.g., MAUI [3]); to full system image migration (e.g., Xen Live Migration [4]). Additionally, all solutions must manage practical issues of mobility such as intermittent and variable connectivity, and the constrained resources of mobile devices.

I will take a *systems approach* to answering these questions, understanding the design space by building and evaluating working prototypes. This approach ensures that the work remains grounded, in terms of both technical feasibility and fulfilment of application requirements. Concretely, I anticipate exploring these spaces using the the Android platform[2] running on the Xen Hypervisor[3] as used by the Amazon EC2 cloud platform.[4] However, note that the knowledge generated by this research will have general applicability to other mobile and virtualization platforms in the form of system architecture, remote access protocols, and scheduling algorithms.

Related Work. Some of the above challenges have been partially addressed, but only independently despite their strong inter-relationship.

Cloud access by mobile devices. Exploration of use of the cloud to provide feature enhancements to existing smartphones has already begun. For example, Clonecloud [5, 6], proposes migration of computation between cloud and device, to provide a variety of "augmented execution" features covering functionality, performance and hardware. More prosaic commercial solutions also exist in this space, e.g., PocketCloud,[5] but these simply provide implementations of standard remote access protocols for mobile devices; they do not take advantage of the possible trade-offs between device and cloud.

Co-scheduling of cloud and mobile resources. Building on a range of work from the past decade under the heading of "cyber-foraging" [7, 8, 9, 10, 11, 12], ongoing projects such as Maui [3] and Erdos [13, 14] address how to enable developers to automatically exploit application mobility to improve performance and battery life. They have addressed neither the third key metric of the financial costs of using the cloud nor whole system behaviour, instead focusing on per-application optimization.

Efficient provision of sensor data to the cloud. Shared sensor network infrastructure has been explored from several viewpoints: multiple competing applications on the mobile device [15];[6] construction of sensor networks from multiple cooperating mobile phones [16]; efficient protocols to coalesce data from large distributed sensor networks [17]. Use of the cloud to provide the dynamic processing resources required by large-scale sensor networks has also been investigated [18]; however, our focus is efficient communication of sensor data (e.g., images, audio, video, location) between the device and its cloud-hosted images, given the resource and timeliness constraints this imposes.

Background. As we enter the era of computer ubiquity, computing devices are steadily moving off the desktop and into our pockets, in the form of phones, tablets, e-readers, &*c*. The mobile phone and its close relative the tablet computer are among the fastest growing consumer-visible computation devices. For example, there are now approximately 4 billion mobile phones in use worldwide, averaging more than two per person in the UK alone. Within this category, it is the smartphone – predominantly Apple's iPhone and iPad devices, plus the many varieties of Android device – that has really revolutionised the use we make of our mobile phones.

Prior to the iPhone, even data-enabled mobile phones were predominantly used for calls and SMS text messaging: discovery and installation of applications was generally fiddly and

[1] http://support.microsoft.com/kb/186607
[2] http://www.android.com
[3] http://www.xen.org
[4] http://aws.amazon.com/
[5] http://www.wyse.co.uk/products/software/pocketcloud/index.asp
[6] EP/G069557/1

time-consuming, with few truly compelling applications available. Subsequently, the introduction of application marketplaces by Apple, Google, and recently Amazon, has revolutionised the way we consume software and use our phones. In addition to changing the market for software in terms of its consumption, it has also radically smoothed the path for developers producing and distributing software for mobile devices..

However, as this revolution continues several issues are becoming apparent. Even with the total control Apple exercise over the iPhone's hardware and software, cases arise where applications for one version do not work on another, e.g., incompatibilities between the iPhone 3g and iPhone 4. The situation is even worse with Android, currently believed to be experiencing the highest growth of any smartphone platform: the open nature of the software and lack of monopolistic control of hardware are important factors in its success but also lead to myriad options and subtle incompatibilities. This fragmentation makes the job of developers much harder, particularly the many small "cottage industry" developers that have arisen in recent years. It also negatively impacts consumer experience when they find that supposedly generic iPhone or Android applications actually fail on their particular device.

There is no indication that this fragmentation will reduce, particularly as device manufacturers continually scramble to release ever faster, more capable devices. This is particularly unfortunate as the relatively high cost of most smartphone devices means that they are often bought subsidised by the network operator on a contract with an 18 month–2 year lock-in. This puts consumers at the whim of the network operator in terms of when they can receive upgrades to hardware and even software, often many months or even years behind e.g., the Android development and release cycle.

Even if one ignores platform-level fragmentation, individuals are still plagued by the need to maintain multiple mobile devices. For example, people commonly need an employer-specific device in addition to their own so that the employer can maintain their infrastructure security perimeter. Inevitably there are problems when the user forgets one device, customises the wrong device, and so on. This is a specific example of a more general problem, that of an individual maintaining different context-specific online identities, e.g., hiding or spoofing their location to certain applications or in certain contexts.

Finally, although the mobile phone has a reasonably high penetration worldwide, the smart phone does not as yet. While many developing nations make extensive use of mobile phone technology, often removing the need for a wired deployment and providing basic services such as banking, they tend to do so with relatively basic devices, several years behind the industrialised west. Although smartphone development proceeds at a rapid pace and prices are constantly falling, it is likely that there will continue to be a substantial gap in device capability for several years to come. This means that many new, exciting applications will remain available only to the richest nations in the world, emphasising existing divides.

Impact. The results of this research will substantially simplify the development ecology as well as reducing the barriers to adoption of new smartphones and upgrades, increasing the inclusivity of these increasingly important technologies. These goals are directly in-line with EPSRC's mission, "advancing knowledge and technology. . . thereby contributing to the economic competitiveness of the United Kingdom." They fit particularly well within the *Digital Economy* priority research area: for example, the Horizon Digital Economy Research Institute will be able to use this platform as the basis both for future technology driven projects *and* business/innovation and social projects (cf. statement of support). By enabling less capable devices such as featurephone to access modern smartphone applications, they are also related to other RCUK research goals, e.g., as addressed in the recent RCUK and Indian Department of Science and Technology call titled "Bridging the Urban and Rural Divide."

I expect this project to generate academic results primarily relevant to the mobile computing, networking and systems communities. As such papers will be submitted to venues such as ACM MobiCom/MobiSys, and ACM/USENIX OSDI/NSDI/SOSP. Talks will also be offered to suitable venues such as Multi-Service Networking, UK Network Operators Forum and the UKERNA Networkshop. Due to the potential wider impact of this work there is also the possibility for inter-disciplinary publication in suitable venues, e.g., Business Models for Mobile Platforms (BMMP) 2011, or the Oxford Journal of Industrial and Corporate Change, in collaboration with, e.g., colleagues within the Horizon Digital Economy Research Institute involved in the funded BURD project *Scaling the Rural Enterprise*.[7]

Impact within and outwith the academic community will be generated by releasing code generated in the course of the project under suitable open-source licenses such as the GPL or AGPL. This maximises likelihood of wider community take-up, while leaving open the door to future commercial exploitation via, e.g., dual-licensing, consultancy services, or spin-out development. Routes to industrial impact will be pursued as they arise, using both my own industrial contacts and the 120+ industrial partners available via Horizon.

Finally there will be impact in training/development via this project. Specifically, the PDRA will be able to enhance and extend existing development skills, with particular emphasis on protocol design including iteration via instrumentation and analysis. The school is also providing support for a home Ph.D. studentship (fees and stipend, with some support available for travel costs and other consumables). The specific thesis topic for the student will be determined in light of their interests and skills, but the initial suggestion will be in the area of measurement and analysis of performance of distributed systems, with a view to developing instrumentation and analysis techniques specific to the mobile-cloud application space. This training and development is in line with, and a first step toward, the aim of building a systems group within the School of Computer Science at the University of Nottingham.

Programme & Methodology The work programme falls into three main sections, mirroring the research aims of the proposal, top and tailed by the initial requirement for certain baseline engineering, and final consolidation activities. As previously noted, the general methodology will use formative evaluation of prototypes to map the design space, as well as to generate outputs including working code artefacts. As a result there is no explicit evaluation work-package: evaluation forms a key part of every research and development work package.

As part of this methodology, management is also not segregated to a separate work package but is threaded throughout the project. Specific activities that will take place include regular weekly or bi-weekly meetings; production of written reports detailing design, implementation and evaluation; and monitoring of appropriate publishing and other dissemination opportunities.

Technical risks surrounding use of Xen, Android and the cloud will be mitigated both through my own expertise and access to that of colleagues in other institutions. Notably, support from Citrix and the main Xen development team will ensure that the work carried out remains informed by and relevant to the leading edge of virtualisation development. Impact risks are mitigated through connections with partners giving rise to impact opportunities (e.g., Citrix, as noted above; University of Nottingham's successful BURD bid); and through tracking of related work to ensure that interesting research results are generated no matter the progress made by other groups.

WP0*. Baseline engineering*

This work package focuses on design and implementation of infrastructure to support execution of Android images on the cloud. Completion of this work package will result in a working Android-on-the-Cloud platform, capable of supporting the main research objectives. As Android natively supports only the ARM architecture, I have carried out some initial feasibility work into using the Android-x86[8] port of Android to the x86 architecture. As a result I have already booted Android 2.3 as a guest domain on the Xen hypervisor.

0.1 Port Android to a commercial cloud infrastructure, e.g., Amazon AWS.[9] *M1*

0.2 Design and implement a simple controller with API to instantiate, activate, configure and quiesce cloud instances. *M2–3*

[7] EP/J000604/1

[8] `http://www.android-x86.org/`

[9] `http://aws.amazon.com/`

***WP1**. Mobile-cloud access protocols*

This work package focuses on scalable protocols to enable the wide range of mobile devices under consideration to leverage the cloud.

1.1 Design and implement simple client software enabling an Android device to instantiate and interact with a copy of itself on the cloud. *M3–4*

1.2 Design and implement a simple protocol and client enabling a capable non-Android device, e.g., iPhone, to use and control a cloud-hosted Android image. *M3–5*

1.3 Design and implement a simple interface allowing less-capable featurephones to interact with a cloud-hosted Xendroid image. For example, a simple web interface, or SMS for control and text output. *M3–6*

***WP2**. Co-scheduling mobile-cloud resources*

Using the platform development from (**WP0**) and the protocols from (**WP1**), enable efficient migration of application execution between the device and the cloud, optimising the trade-off between the three key parameters of performance, battery life and the direct monetary costs of using the cloud.

2.1 Extend the API of (**WP0.2**) to support extraction of statistics, incurred costs, &*c*., for scheduling. *M6*

2.2 Instrument and evaluate the protocols developed in (**WP1**) to provide data informing future optimisation. *M6–8*

2.3 Using this data develop scheduling techniques to optimise location of application execution, considering cost, performance, battery-life as primary resources. *M8–12*

***WP3**. Access to sensor data*

3.1 Extend protocols of (**WP1**) to include sharing of device resources, e.g., sensor data streams, private data, between multiple applications running on the cloud-hosted image. *M10–12*

***WP4**. Consolidation*

Although publication opportunities will be pursued as they arise, a final consolidation work package will ensure that all knowledge generated is recorded and able to be exploited in follow-on work.

4.1 Consolidate code artefacts for release. *M13–15*

4.2 Produce final documentation and writeups for appropriate submission. *M13–15*

4.3 Work with partners to transfer knowledge from this project. *M9–15*

4.4 Generate future proposals. *M6–15*

References

[1] T. Richardson, Q. Stafford-Fraser, K. R. Wood, and A. Hopper. Virtual network computing. *IEEE Internet Computing*, 2(1):33–38, January 1998.

[2] R. Scheifler and J. Gettys. *X Window System: Core and Extension Protocols*. Butterworth-Heinemann, Oxford, 1997.

[3] E. Cuervo, A. Balasubramanian, D.-k. Cho, A. Wolman, S. Saroiu, R. Chandra, and P. Bahl. MAUI: making smartphones last longer with code offload. In *Proceedings of the 8th international conference on Mobile systems, applications, and services*, MobiSys '10, pp. 49–62, New York, NY, USA, 2010. ACM.

[4] C. Clark, K. Fraser, S. Hand, J. G. Hansen, E. Jul, C. Limpach, I. Pratt, and A. Warfield. Live migration of virtual machines. In *USENIX Symposium on Networked Systems Design & Implementation (NSDI)*, pp. 273–286, Berkeley, CA, USA, 2005. USENIX Association.

[5] B.-G. Chun and P. Maniatis. Augmented smartphone applications through clone cloud execution. In *Proceedings of the 12th conference on Hot topics in operating systems*, HotOS'09, pp. 8–8, Berkeley, CA, USA, 2009. USENIX Association.

[6] B.-G. Chun, S. Ihm, P. Maniatis, M. Naik, and A. Patti. Clonecloud: Elastic execution between mobile device and cloud. In *Proceedings of the 6th European Conference on Computer Systems (EuroSys)*, April 2011. To appear.

[7] J. Sousa and D. Garlan. Aura: an architectural framework for user mobility inubiquitous computing environments. In *Proc. of the 3rd Working IEEE/IFIP Conference on Software Architecture*, 2002.

[8] R. K. Balan, M. Satyanarayanan, S. Park, and T. Okoshi. Tactics-based remote execution for mobile computing. In *Proc. of The 1st International Conference on Mobile Systems, Applications, and Services*, pp. 273–286, 2003.

[9] R. Balan, J. Flinn, M. Satyanarayanan, S. Sinnamohideen, and H. Yang. The case for cyber foraging. In *Proc. of the 10th ACM SIGOPS European Workshop*, 2002.

[10] B. Noble, M. Satyanarayanan, D. Narayanan, J. Tilton, J. Flinn, and K. Walker. Agile application-aware adaptation for mobility. In *Proc. of the ACM Symposium on Operating System Principles (SOSP)*, 1997.

[11] O. R. J. Porras and M. D. Kristensen. *Dynamic Resource Management and Cyber Foraging*, chapter Middleware for Network Eccentric and Mobile Applications. Springer Press, 2008.

[12] A. L.-C. Niraj, N. Tolia, R. Balan, E. D. Lara, and M. Satyanarayanan. Dimorphic computing. Technical Report CMU-CS-06-123, Carnegie Mellon University, School of Computer Science, April 2006.

[13] N. Vallina-Rodriguez, P. Hui, J. Crowcroft, and A. Rice. Exhausting battery statistics: understanding the energy demands on mobile handsets. In *MobiHeld '10: Proceedings of the second ACM SIGCOMM workshop on Networking, systems, and applications on mobile handhelds*, pp. 9–14, New York, NY, USA, 2010. ACM.

[14] N. Vallina-Rodriguez and J. Crowcroft. Erdos: An energy-aware social operating system for mobile handsets. In *Proceedings of ACM/USENIX OSDI*, Vancouver, BC, Canada, October 2010. Poster.

[15] C. M. Christos Efstratiou, Ilias Leontiadis and J. Crowcroft. Demo abstract: A shared sensor network infrastructure. In *Proceedings of SenSys*, November 2010.

[16] A. Kansal, M. Goraczko, and F. Zhao. Building a sensor network of mobile phones. In *Proceedings of Information Processing in Sensor Networks (IPSN)*, April 2007.

[17] J. Agre and L. Clare. An integrated architecture for cooperative sensing networks. *IEEE Computer Magazine*, 33:106–108, May 2000. `10.1109/2.841788`.

[18] K. Lee, D. Murray, D. Hughes, and W. Joosen. Extending sensor networks into the cloud using amazon web services. In *Proceedings of the IEEE International Conference on Networked Embedded Systems for Enterprise Applications (NESEA)*, November 2010.

Horizon Transitional Fellowship. I have been Horizon Transitional Fellow in Computer Science since Nov/2009. The Horizon Digital Economy Research Institute provides a broad, collaborative research environment in which I am developing as an early career researcher. This includes access to a wide range of expertise as well as over a hundred commercial project partners.

As Transitional Fellow, I have been instrumental in shaping the technical direction of Horizon to date. In addition to being co-investigator on several Horizon projects, I currently lead the £115,000 *Personal Containers* project, a core piece of Horizon infrastructure exploring means to manage and exploit our personal data [1]. Through design and evaluation of prototypes, we are developing an understanding of the requirements on systems to process personal data; in the light of this understanding, we are also designing and building federated systems for third-party processing of our personal data as it becomes ever deeper and broader.

Projects outside Horizon in which I am currently active are building other infrastructures required by the digital economy: (*i*) developing novel home network protocols and technologies, extending the ability of non-technical home owners to manage their connectivity [2]; and (*ii*) developing novel operating systems and programming environments using functional programming tools, to improve performance, reliability and productivity of cloud computing environments [3, 4].

Co-founder, Vipadia LImited. Before returning to academia I spent 2 years as co-founder of Vipadia Limited, a startup specialising in voice-on-IP and related network consultancy. While with Vipadia I designed and built the Karaka[1] and Clackpoint[2] products which were subsequently acquired by Voxeo Corp., FL, USA. *Karaka* is a scalable Skype–XMPP gateway, bridging the Skype and Google Talk messaging networks. *Clackpoint* is a protocol-agnostic multi-party conferencing service, enabling web-designers and application developers to easily embed conferencing facilities within their products. Six months after launch Clackpoint was servicing 160,000 unique users/month.

Microsoft Research. I was a full-time researcher with the Systems and Networking Group at Microsoft Research (MSR) Cambridge between March 2002 and January 2008. My focus was understanding the performance of large networked systems in order to radically improve their resource management. In pursuit of this I performed research in communications, processing and data management, ranging across networking, operating systems (OSs) and databases, resulting in top-tier publications in database systems, network management, network architecture and OS resource control. Notable features of my work are its solid grounding in real data gathered from real systems and networks, and that it is collaborative, both nationally and internationally. Key publications deriving from work during this period include [5, 6, 7, 8, 9, 10], in addition to 5 patents.

Sprint ATL. Prior to joining Microsoft, I worked for 6 months at one of the worlds top IP network research groups, the IP Group at Sprint Advanced Technology Lab (ATL) in California. I implemented a routing data collection and analysis system that ran continuously for over 3 years against Sprintlink, Sprint's tier-1 backbone IP network. Subsequently used widely in the community, it led directly to two of my papers which were among the first of their kind: one analysing network link failures and their subsequent impact on new applications such as Voice-over-IP [11]; and the other examining the appearance and impact of loops in Internet routing [12].

University of Cambridge. I completed my Ph.D. with the Systems Research Group at the Cambridge University Computer Lab, after achieving a distinction in the Diploma in Computer Science from the Cambridge University Computer Laboratory, and a 2.(i) in Mathematics, also from Cambridge University. As my Ph.D. was funded through a CASE award from BT, I was responsible for the Cambridge University contribution to LEARNET, a multi-institution project involving BT, Cambridge, and UCL. Following on from this I instantiated, managed and completed the Marconi-funded Efficient Network Control project which developed from my thesis work.

[1] `http://github.com/mor1/karaka/`
[2] `http://clackpoint.com`

References

[1] D. McAuley, **R. Mortier**, and J. Goulding. The Dataware Manifesto. In *Proceedings of the 3rd IEEE International Conference on Communication Systems and Networks (COMSNETS)*, Bangalore, India, January 2011. Invited paper.

[2] J. Sventek, A. Koliousis, O. Sharma, N. Dulay, D. Pediatitakis, M. Sloman, T. Rodden, T. Lodge, B. Bedwell, K. Glover, and **R. Mortier**. An information plane architecture supporting home network management. In *Proceedings of IFIP/IEEE International Symposium on Integrated Network Management (IM)*, Dublin, Ireland, May 2011.

[3] A. Madhavapeddy, **R. Mortier**, J. Crowcroft, and S. Hand. Multiscale not multicore: efficient heterogeneous cloud computing. In *Proceedings of the 2010 ACM-BCS Visions of Computer Science Conference (ACM-BCS'10)*, pp. 1–12, Edinburgh, United Kingdom, 2010. British Computer Society.

[4] A. Madhavapeddy, **R. Mortier**, R. Sohan, T. Gazagnaire, S. Hand, T. Deegan, D. McAuley, and J. Crowcroft. Turning down the lamp: Software specialisation for the cloud. In *Proceedings of the 2nd USENIX Workshop on Hot Topics in Cloud Computing (HotCloud)*, Boston, MA, USA, June 2010. USENIX.

[5] P. Barham, A. Donnelly, R. Isaacs, and **R. Mortier**. Using Magpie for request extraction and workload modelling. In *Proceedings of the 6th Symposium on Operating Systems Design & Implementation (OSDI)*, pp. 259–272, San Francisco, CA, USA, December 2004. USENIX.

[6] E. Cooke, **R. Mortier**, A. Donnelly, P. Barham, and R. Isaacs. Reclaiming network-wide visibility using ubiquitous endsystem monitors. In *Proceedings of the USENIX Annual Technical Conference*, pp. 357–362, Berkeley, CA, USA, June 2006. USENIX.

[7] T. Karagiannis, **R. Mortier**, and A. Rowstron. Network exception handlers: Host-network control in enterprise networks. In *Proceedings of ACM SIGCOMM 2008*, pp. 123–134, Seattle, WA, USA, August 2008. ACM.

[8] D. Narayanan, A. Donnelly, **R. Mortier**, and A. Rowstron. Delay aware querying with Seaweed. *The VLDB Journal*, 17(2):315–331, March 2008. `http://dx.doi.org/10.1007/s00778-007-0060-3`.

[9] T. Karagiannis and **R. Mortier**. Address and traffic dynamics in a large enterprise network. In *Proceedings of the 16th IEEE Workshop on Local and Metropolitan Area Networks (LANMAN)*, pp. 102–107, Chij-Napoca, Transylvania, September 2008. IEEE.

[10] D. Fay, H. Haddadi, A. Thomason, A. Moore, **R. Mortier**, A. Jamakovic, S. Uhlig, and M. Rio. Weighted Spectral Distribution for Internet topology analysis: Theory and applications. *IEEE/ACM Transactions on Networking (TON)*, 18(1):164–176, February 2010. `http://dx.doi.org/10.1109/TNET.2009.2022369`.

[11] G. Iannacone, C. Chuah, **R. Mortier**, S. Bhattacharyya, and C. Diot. Analysis of link failures in an IP backbone. In *Proceedings of the Second ACM SIGCOMM Internet Measurement Workshop (IMW)*, pp. 237–242. ACM, November 2002. Short paper. Also available as Sprint ATL Technical Report TR02-ATL-051025, May 2002.

[12] U. Hengartner, S. Moon, **R. Mortier**, and C. Diot. Routing loops: Detection and analysis of their impact on loss and delay. In *Proceedings of the Second ACM SIGCOMM Internet Measurement Workshop (IMW)*, pp. 107–112. ACM, November 2002. Short paper. Also available as Sprint ATL Technical Report TR02-ATL-051001, May 2002.

This project is planned for 15 months and I am requesting £124,994 (100% fEC) [£99,995 (80% fEC)] in support from the EPSRC. Figures in the following justification are quoted at 100% fEC values.

Directly allocated. I request resources to cover salary costs of 4 hours/week of the PI (myself, Dr. Richard Mortier) reflecting the management and design responsibility within this project. Including all associated on-costs, this amounts to £7,213.

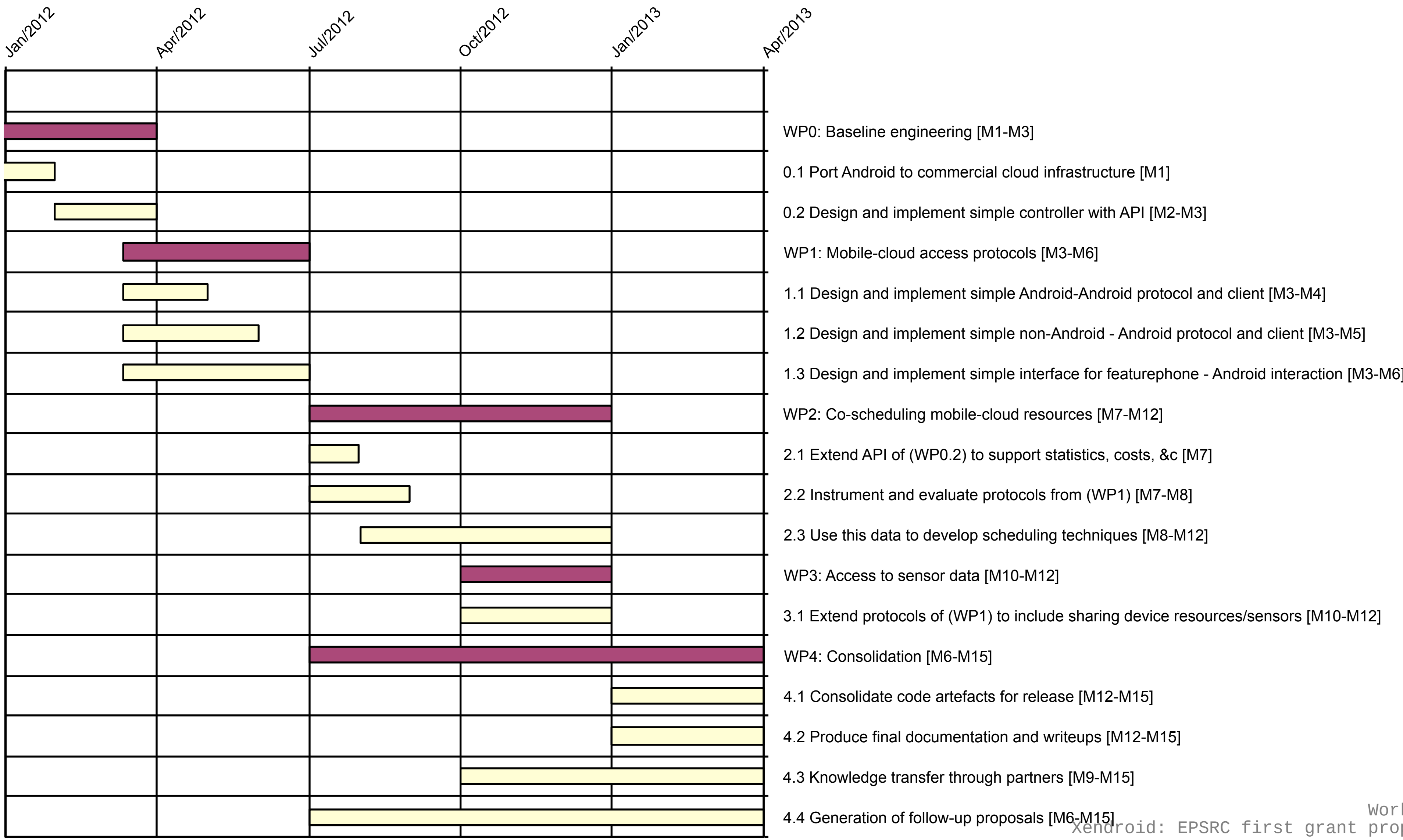
Directly incurred: staffing. I request resource to cover a full-time post-doctoral research fellow who will carry out a significant amount of the practical implementation and evaluation work within the project. Including all associated on-costs, this amounts to £49,813.

Directly incurred: equipment/consumables. I request a total of £1,500 to cover a high-spec laptop and docking station for the research fellow to use directly as a development machine for mobile device client software, as well as to access existing server resources for development of the server-side counterpart software.

Initial development will primarily be carried out using existing resources from the School of Computer Science. The development process will utilise distributed version control, backup and deployment in the cloud via the GitHub and Amazon EC2 services: this is costed at £1,025 over the lifetime of the project. Extra hardware resources in the form of the key mobile devices are required in order to develop and test client software for mobile devices: this includes Apple iPhone/iPad, Android phone and tablet, and legacy feature phone platforms, and totals £3,028 including airtime for the mobile phones and tablet devices. Additional development devices will be made available by both Horizon and the School of Computer Science where necessary.

Directly incurred: travel & subsistence. I request a total of £3,417 to cover travel and subsistence associated with dissemination of results at national (two) and international (one) venues. I request funding for an international conference as conferences in systems and networking are typically USA-based.

Estates and indirect costs. Estates, indirect and infrastructure technician costs totalling £58,998 are requested – these figures have been calculated using rates agreed between The University of Nottingham and the Research Councils.



Jan/2012
Apr/2012
Jul/2012
Oct/2012
Jan/2013
Apr/2013
WP0: Baseline engineering [M1-M3]
0.1 Port Android to commercial cloud infrastructure [M1]
0.2 Design and implement simple controller with API [M2-M3]
WP1: Mobile-cloud access protocols [M3-M6]
1.1 Design and implement simple Android-Android protocol and client [M3-M4]
1.2 Design and implement simple non-Android - Android protocol and client [M3-M5]
1.3 Design and implement simple interface for featurephone - Android interaction [M3-M6]
WP2: Co-scheduling mobile-cloud resources [M7-M12]
2.1 Extend API of (WP0.2) to support statistics, costs, &c [M7]
2.2 Instrument and evaluate protocols from (WP1) [M7-M8]
2.3 Use this data to develop scheduling techniques [M8-M12]
WP3: Access to sensor data [M10-M12]
3.1 Extend protocols of (WP1) to include sharing device resources/sensors [M10-M12]
WP4: Consolidation [M6-M15]
4.1 Consolidate code artefacts for release [M12-M15]
4.2 Produce final documentation and writeups [M12-M15]
4.3 Knowledge transfer through partners [M9-M15]
4.4 Generation of follow-up proposals [M6-M15]

The University of Nottingham

School of Computer Science
Jubilee Campus
Wollaton Road
Nottingham
NG8 1BB

Tel +44 (0)115 951 4251
Fax +44 (0)115 951 4254

www.nottingham.ac.uk/cs/

Head of School:
Professor Steve Benford

23 May 2011

TO WHOM IT MAY CONCERN

Host organisation statement in support of Dr Richard Mortier's EPSRC first grant proposal (Ref.23070)

"Xendroid: Cloud-hosting Your Mobile Devices"

The School of Computer Science strongly supports this proposal from Dr Richard Mortier on the topic of 'Cloud-Hosting Your Mobile Devices'. Dr Mortier's has been a key strategic appointment within the School and also our Horizon Digital Economy Research Centre to grow our interests in distributed systems support for new digital economy services and this proposal is an important step towards realising this. The School and Horizon will be supporting this proposal in the following specific ways:

- By funding an associated dedicated PhD student as described in the proposal
- Through access to a further pool of PhD students through his involvement in the Horizon Doctoral Training Centre
- By enabling him to draw on other resources to promote both the academic and industrial impact of the work, including extensive travel and equipment resources, a network of industry partners, and mechanisms such as Horizon's innovation workshops, run in conjunction with our Business School
- He will receive extensive support from colleagues including his personal mentor within the School as well as a cohort of colleagues within Horizon, the Schools Research Strategy Group, and training on the PGCHE programme
- Through a light teaching and administrative load during his early years in post so that he can best develop his research. This is a formal arrangement as part of his 'transitional fellowship' post which sees him making the transition to a full academic load over a five year period

Dr Mortier is an extremely promising researcher and we most strongly support this innovative and industrially relevant proposal.

SDBenford

Professor Steve Benford
Head of School of Computer Science

Nottingham