The Human Element as the Key Enabler of Pervasiveness

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***Abstract*—The recent proliferation of sensor-equipped smartphones has brought sensor networking to the general public in the form of mobile phone sensing. By reaching out to mainstream users, mobile phone sensing has the potential of achieving the pervasive computing vision by putting the human element in the foreground. Because mobile phone sensing may require computationally intensive applications, it is impractical and inefficient to stick to local processing. On the other hand, the emerging trend of offloading expensive tasks to the mobile computing cloud has a significant energy footprint and suffers from the drawbacks of extreme centralization. Opportunistic computing provides an appealing alternative to the mobile computing cloud by allowing devices to join forces and leverage heterogeneous resources from other devices. Because this is only possible by leveraging human mobility, opportunistic computing adds even more prominence to the role of the human element, which is already central to mobile phone sensing and now becomes the key enabler of pervasiveness.**

I. Introduction

In the pervasive vision, processing and communication capabilities are ubiquitously embedded in our world so that information can be produced and consumed pervasively. Back in 1991 [1], Mark Weiser's dream of a ubiquitous technology that would permeate everyday life and become transparent to human users was certainly visionary, but only five years later Mark Weiser predicted that the cross-over point of ubiquitous computing and PC would occur between 2005 and 2020 [2]. Since then, mobile phones have become ubiquitous, and we are now witnessing the proliferation of smartphones, whose wireless market share in the US was already past 20% by the end of 2009 and whose sales are expected to surpass desktop PCs in 2011 [3], which would confirm Mark Weiser's prediction.

In this paper, we begin by looking back at the quest for pervasiveness, from the pure Mobile Ad hoc NETworks (MANET) model to application-driven wireless sensor networking, and to the rapidly growing field of mobile phone sensing, which brings pervasiveness to the masses by leveraging the human element. After delving into the central role of the human element, we focus on the pervasive opportunities that it opens up in combination with opportunistic computing.

II. Towards Ubiquitous and Pervasive

A. MANETs and the Ubiquitous Vision

Until the beginning of the century, MANETs were viewed as the most promising solution for the implementation of the Ubiquitous and Pervasive Computing vision. Pure MANETs are networks of mobile nodes that exchange information wirelessly in the absence of a fixed infrastructure. Despite the countless research efforts in the field of MANETs, it has become clear over the past decade that their general-purpose, infrastructure-free, and unrealistically scalable basic paradigm was not conducive to the implementation of a vision that sought to reach out to mainstream users. Starting around 2004, it was understood that the scarce impact of MANETs was not due to their networking paradigm per se, but was the direct consequence of the research directions adopted. Precisely, MANET research specialized in military and emergency response applications where no infrastructure is available, high operational costs are tolerated, and scalability is crucial. This overspecialization made MANETs a poor fit to the needs of mainstream users who

978-1-4577-0899-2/11/$26.00

demand Internet connectivity and have no interest in an isolated, self-configured network.

More pragmatic *hybrid MANET* approaches have emerged as a consequence of the relaxation of the *no infrastructure* constraint of the pure MANET paradigm [4]. Far from being isolated networks, hybrid MANETs represent flexible extensions of the Internet whose main goal is to offer connectivity to mainstream users beyond the constraints of the wired infrastructure and the radio range of access points. The hybrid MANET paradigm has been boosted by the success of wireless mesh networks [5], hierarchical networks where a limited number of access points provide Internet connectivity to mobile users by way of multihop communication over a scalable number of mesh routers that create a wireless backbone. Thanks to mesh networks, mobile users located far from an access point can still access the Internet over multiple hops over the wireless backbone. Nonetheless, despite their commercial appeal and wide applicability, mesh networks are a poor fit for a pervasive scenario with high user mobility and intermittent connectivity.

B. Sensor Networks: Scenario-driven Pervasiveness

Another major roadblock for MANET research was its focus on general-purpose networks and lack of application-driven and experimental research (and abundance of unrealistic simulation work [6]). Originally a spinoff of MANETs, Wireless Sensor Networks used a radically different line of attack that was mostly platform- and application-driven [7]. Initially fueled by the Smart Dust vision [8], [9], and largely centered around the resource-constrained yet versatile and flexible Berkeley mote platform, the sensor network community has produced a decade's worth of rich and innovative research. Although, in principle, sensor networks are very close to the pervasive vision, their pervasiveness is always scenario-driven. Most sensor networks involve some form of monitoring and pervade the specific scenario that they are designed to monitor, be it a volcano [10], a bridge [11], a smart building [12], or a person's body [13]. Although the application spectrum of sensor networks is extremely wide, the motes never caught the attention of mainstream users because they do not offer a killer service that would appeal to the masses. Far from pervading people's lives, motes are inherently meant to keep people out of the loop.

The mobile phone was initially viewed as a high-end gateway-like device that could interface a sensor network with the outside world and take care of advanced processing tasks that could not be handled by low-end motes; representative efforts in this direction include the Phone System Interface board [14] (a sensor network gateway that plugs into the MMC/SD-card socket of a phone), the Healthgear system [15], whose wearable low-end sensor nodes use Bluetooth to communicate to a cell phone that processes their data, and Bikenet [16], where several bicycle- and human-mounted low-end motes report to a mobile phone through an 802.15.4-to-Bluetooth interface. Compared to low-end motes, the mobile phone was viewed as a higher-end device with a lot more computing power and much more relaxed energy constraints. With the recent transition from the feature phone to the smartphone [17][18], the mobile phone itself has extensive sensing capabilities and can therefore double as a mobile sensing device.

Thanks to advances in Micro-Electro-Mechanical Systems (MEMS), mobile phones can now incorporate miniaturized sensors without sacrificing their compact form factor. they Smartphones represent an ideal platform for any human-centric sensing application [19] because of their programmability, their flexibility, and their extensive application distribution opportunities. Various aspects of Smartphone-centric mobile networking have been explored within the MetroSense project [20] at Darmouth and the Urban Sensing projects [21] at UCLA. Because of their ability to leverage on the human element, smartphones can now be considered the number one candidate for the achievement of the pervasive vision [22] and give a prominent role to the human element.

III. The Human Element

Like the PC brought computing to the general public, mobile phone sensing brings sensor networking to the masses: the key components of sensing, computing, and communication are already out there as ubiquitous commercial products carried by humans. The human element is central to mobile phone sensing: indeed, smartphones are enabling a human-centric sensor networking paradigm [19]. Smartphones allow the option to keep humans in the loop, as is the case with the *participatory sensing* [23] approach pioneered by UCLA, or out of the loop, as with Dartmouth's *opportunistic sensing* [19]; with either model of human involvement, humans are the focus of mobile sensing systems. By and large, the participatory and opportunistic paradigms are complementary forms of human-centric sensing (as noted in [19]), and human-centric sensing itself is, for the most part, complementary to mote-based sensing. Mote-based sensor networks may not ever turn into a mainstream commodity, but they will remain a powerful tool for domain scientists whose applications do not require (or do not want) people to be in the loop. For large-scale sensing applications, however, the opportunistic sensing model is the most practical, because it does not require the active involvement of the human user [24].

Mobile phone sensing is intrinsically tied to the uncontrollable mobility of humans. If a mobile device is asked to carry out a sensing task in a given area, it may not be anywhere near the area of interest, or it may not be equipped with the right sensors [25]. Opportunistic techniques can help: sensory data from the area of interest or from devices with the right sensors may be collected and processed opportunistically. Because human mobility enables opportunistic communication, special attention has been devoted to understanding its properties. In [26], a human mobility model is proposed that encompasses three key properties that are isolated out of a vast body of recent work: human mobility heavily depends on social relations, users spend most of their time at a few locations, and short trips are the rule while long ones are the exception. Since naive forwarding strategies have been shown not to work for opportunistic networking [27], it has been proposed to exploit the prediction and exploitation of human mobility patterns to streamline forwarding [28].

As illustrated in [22], smartphones have been equipped with sensors to improve some aspect of the user's phone experience: accelerometers and gyroscopes [29] are used to detect the orientation of the phone (to adjust the display or to enhance the gaming experience), light sensors serve to adjust the brightness of the display, and proximity sensors detect whether the phone is close enough to the user's face so that the touchscreen may be turned off. Other sensors such as microphones, cameras, and the GPS have been included to provide complementary services. Specifically, the GPS is instrumental to the emerging must-have feature of navigation, which also requires the presence of an electronic compass [30]. Finally, other sensors have been added for diagnostics; this is the case of the controversial Liquid Contact Indicators of the iPhone, used by Apple to void warranties on misused phones but allegedly prone to false positives.

Mobile phone sensing is opening up several avenues for the achievement of the pervasive vision, and such new pervasive opportunities are intimately tied to the human element.

IV. Pervasive Opportunities

A. A Distributed Cloud

Architectural solutions for mobile phone sensing systems still remain the subject of open research [22]. Because smartphones can generate large volumes of heterogeneous sensory data whose processing requires abundant computing power, it has been suggested that a mobile phone sensing architecture should rely on the mobile computing cloud [22], so that a smartphone can outsource resource-intensive tasks to a remote high-performance computing system reachable over the Internet. On one hand, the idea of remote execution [31] and cyber-foraging [32] are an integral part of pervasive computing, and relying on the mobile computing cloud appears to be a natural solution [22], because mobile wireless devices will always remain relatively resource-constrained compared to their fixed counterparts. As an example, the CloneCloud system [33] leverages execution migration techniques to clone a smartphone's state to the cloud so that computationally-intensive applications are run on a virtual smartphone clone within the cloud before reintegrating the results from the cloud back into the actual smartphone. On the other hand, the high-performance computing resources that form the computing cloud are typically available at a remote location, and the energy footprint of the data transfer may be significant [34]. At the other end of the offloading spectrum we find systems, like

Soundsense [35], where all tasks are run locally on the smartphone and are therefore constrained by its relatively scarce resources. Because continuous sensing takes a huge toll on the energy reserves of a phone, it has been suggested to offload sensing tasks to a dedicated low-power co-processor. This is the approach followed by the Little Rock architecture [36], where the use of an MSP430 processor (the same as in TelosB) allows dramatic energy-savings.

To address the inherent resource-poverty of mobile terminals along with the setbacks of relying on distant clouds, the *cloudlet* model [37] has been proposed: mobile terminals can leverage cloudlets of nearby infrastructure that can be accessed over Wi-Fi. This is certainly a promising strategy, especially given the recent results on the advantages of augmenting 3G with Wi-Fi [38]. The Mobile Assistance Using Infrastructure (MAUI) system [39] has been recently proposed to enable the fine-grained energy-aware offload of code from a mobile device to a MAUI node, *i.e.*, a nearby piece of infrastructure connected to the mobile device by a high-performance WLAN link. It is shown in [39] that the cost of 3G for code offloads is prohibitive compared to Wi-Fi, and that the energy consumption of code offloads grows almost linearly with the Round Trip Time (RTT): using a nearby server is much more beneficial and energy-efficient than using a distant cloud, which confirms the conclusions in [37].

Given that small clouds in the neighborhood are better than a distant big cloud, why not further break up the cloud? By adopting opportunistic computing [40], [41], pervasive devices can opportunistically tap on each other's resources and access each other's services, or even combine each other's resources. The combination of resources has already been studied in the context of the MobiUS architecture [42] and its better-together paradigm, which focuses on close proximity networking between pairs of devices. Opportunistic computing can be viewed as a radical generalization of both the MobiUS and the cloudlet/MAUI approach: services can be combined across multiple nodes, are offered by any node, and can be offloaded to any node (and not just a special subset of infrastructure nodes). As shown in Figure 1, opportunistic computing offers a *distributed cloud*, *i.e.*, a computing system that harnesses the CPU, memory, energy, and sensing resources of multiple nodes of heterogeneous capabilities that collectively form a cloud that is distributed in both space and time. Each node in the distributed cloud corresponds to a pairwise encounter, and may therefore provide useful local context information, which is something that a distant computing cloud would not be able to give. Opportunistic computing also avoids the centralization of cloud computing, with significant benefits in terms of security and reliability. The time-distributed nature of the opportunistic cloud is the direct byproduct of its opportunistic networking blueprint: an end-to-end path typically does not exist between any node pair at any given time, but can be achieved through node mobility over time. The dependency of the opportunistic cloud on mobility is directly tied to its dependency on the human element.

B. Opportunistic Networking and Computing

Because the pervasive vision revolves around the human user, it can only be achieved by a flexible networking paradigm that adapts to the user instead of expecting the user to adapt. Human users move around freely and cannot be expected to always be within range of an access point or a mesh router. On the other hand, humans are social by nature, and they can very well be expected to come in contact with each other with a relatively high frequency; it is this very expectation that constitutes the basic tenet of *opportunistic networking*.

In opportunistic networks [43], node-to-node communication occurs by exploiting any tidbit of connectivity that becomes available. Nodes in an opportunistic network rely on pairwise encounters and a store-and-forward paradigm to send information to each other over multiple hops even in the absence of an end-to-end path. Opportunistic communication is possible as long as there are forwarding opportunities. By breaking away from any end-to-end path requirement, opportunistic networks lend themselves to the pervasive vision by making connectivity available anywhere and anytime, though not all the time. Any user can exchange data with any other user from any location at any time, as long as she is not a hermit and is in no hurry. Opportunistic networks allow information to flow to its destination through the combined use of network connectivity and node mobility. Mobility is no longer viewed as a disruptive phenomenon that thwarts the laborious routing process, but as a benefit that streamlines communication by offering new data exchange opportunities between nodes. Mobility enables nodes to come in contact with other nodes and makes it more likely for them to encounter useful forwarders that can get their messages closer to its intended destination.

The proliferation of mobile devices over the past decade has dramatically increased the opportunities for those pairwise contacts between devices that make opportunistic networking possible. Just like pairwise contacts may be exploited to exploit connectivity opportunistically, they can also be used to exploit services and resources: this is the basic premise to the jump from opportunistic networking to opportunistic computing [40], [41]. In essence, opportunistic computing can be viewed as delay-tolerant distributed computing without continuous end-to-end connectivity between any node pair [40]. Opportunistic networking is in fact leveraged to run distributed computing services by getting multiple devices to join forces. While opportunistic computing can be implemented across different classes of devices, smartphones are likely to be the main driving platform. Smartphones combine the functionalities of Personal Digital Assistants (PDAs) and feature cellular phones, and come equipped with an ever richer sensory suite that has already led to the emergence of mobile phone sensing systems, *i.e.*, smartphone-centric sensor networks that rely on the human element.

Over the past few years, the European Commission (EC) has funded several research efforts that significantly furthered our understanding of opportunistic networking. Specifically, the EC ran a dedicated program on Future and Emerging Technologies (FET) within the priority area on Information Society Technology (IST) of its Sixth Framework Program (FP6). Key advances in opportunistic networking were obtained by IST-FET projects Haggle [44] and ANA (Autonomic Network Architecture) [45]. Within the EC's Seventh Framework Program (FP7), the SCAMPI (Service platform for soCially Aware Mobile and PervasIve computing) [46] project is now exploring opportunistic computing.

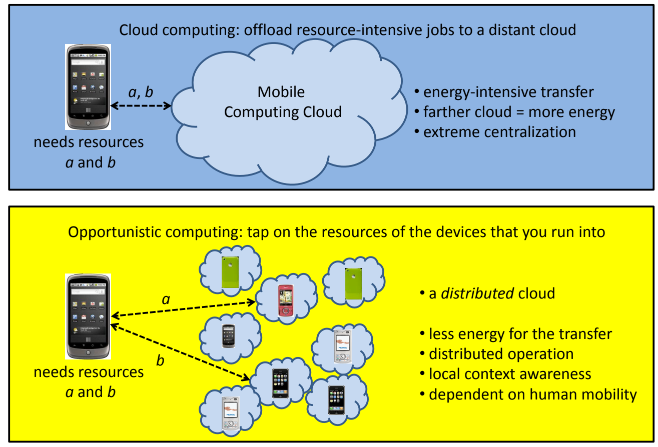

Fig. 1. Opportunistic computing breaks up the computing cloud.

V. Conclusion

Mobile networks of sensor-rich smartphones are leading us toward Mark Weiser's pervasive vision. Going forward, it will be critical to identify the architectural solutions that best lend themselves to the extraction and processing of human-centric sensory data. The exclusively local execution of computationally intensive tasks is necessarily a sub-optimal approach. At the opposite end of the local versus remote execution tradeoff, cloud computing offers high-end resources at a non-negligible energy cost and with the risks that are typical of extreme centralization. We believe that opportunistic computing may offer the best of both worlds: individual devices may combine and exploit each other's resources to boost their computing power and overcome the limitations of their own resources without the communication energy footprint and the extreme centralization of cloud computing. Of course, this is only possible as devices come in contact thanks to human mobility. Being central to mobile phone sensing as well as opportunistic techniques, the human element is now acting as the key enabler of pervasiveness.

References

[1] M. Weiser. The Computer for the Twenty-First Century. In *Scientific American*, pages 94–100, September 1991.

[2] M. Weiser and J. Brown. The coming age of calm technology. In *Beyond Calculation: the Next Fifty Years*, pages 75–85, New York, NY, USA, 1997. Copernicus.

[3] H. Falaki, R. Mahajan, S. Kandula, D. Lymberopoulos, R. Govindan, and D. Estrin. Diversity in Smartphone Usage. In *5th Annual International Conference on Mobile Systems, Applications and Services (MobiSys'10)*, San Francisco, CA, USA, June 2010.

[4] M. Conti and S. Giordano. Multihop Ad Hoc Networking: The Reality. In *IEEE Communications Magazine*, pages 88–95, April 2007.

[5] R. Bruno, M. Conti, and E. Gregori. Mesh Networks: Commodity Multihop Ad Hoc Networks. In *IEEE Communications Magazine*, pages 123–131, March 2005.

[6] S. Kurkowski, T. Camp, and M. Colagrosso. Manet simulation studies: the incredibles. *SIGMOBILE Mobile Computing Communication Review*, 9(4):50–61, 2005.

[7] D. Puccinelli and M. Haenggi. Wireless Sensor Networks-Applications and Challenges of Ubiquitous Sensing. *IEEE Circuits and Systems Magazine*, 5:19–29, August 2005.

[8] B. Warneke, M. Last, B. Leibowitz, and K.S.J. Pister. Smart Dust: Communicating with a Cubic-Millimeter Computer. *IEEE Computer*, pages 44–51, June 2001.

[9] J. Hill, M. Horton, R. Kling, and L. Krishnamurthy. The Platforms enabling Wireless Sensor Networks. *Communications of the ACM*, 47:41–46, June 2004.

[10] G. Werner-Allen, K. Lorincz, O. Marcillo, J. Johnson, J. Lees, and M. Welsh. Deploying a Wireless Sensor Network on an Active Volcano. *IEEE Internet Computing*, March-April 2006.

[11] S. Kim, R. Fonseca, P. Dutta, A. Tavakoli, D. Culler, P. Levis, S. Shenker, and I. Stoica. Flush: a reliable bulk transport protocol for multihop wireless networks. In *5th ACM Conference on Embedded Networked Sensor Systems (SenSys'07)*, Sydney, Australia, November 2007.

[12] L. Schor, P. Sommer, and R. Wattenhofer. Towards a zero-configuration wireless sensor network architecture for smart buildings. In *1st ACM Workshop On Embedded Sensing Systems For Energy-Efficiency In Buildings (BuildSys'09)*, Berkeley, CA, USA, November 2009.

[13] M. Hanson, H. Powell, A. Barth, K. Ringgenberg, B. Calhoun, J. Aylor, and J. Lach. Body Area Sensor Networks: Challenges and Opportunities. *IEEE Computer*, 42:58–65, January 2009.

[14] T. Pering, P. Zhang, R. Chaudhri, Y. Anokwa, and R. Want. Healthgear: A real-time wearable system for monitoring and analyzing physiological signals. In *International Workshop on Wearable and Implantable Body Sensor Networks (BSN'06)*, April 2007.

[15] N. Oliver and F. Mangas. Healthgear: A real-time wearable system for monitoring and analyzing physiological signals. In *International Workshop on Wearable and Implantable Body Sensor Networks (BSN'06)*, April 2006.

[16] S. Eisenman, E. Miluzzo, N. Lane, R. Peterson, G. Ahn, and A. Campbell. The BikeNet Mobile Sensing System for Cyclist Experience Mapping. In *5th ACM Conference on Embedded Networked Sensor Systems (SenSys'07)*, Sydney, Australia, November 2007.

[17] S. Olsen. When to Buy Your Child a Cellphone. *The New York Times*, 9 June 2010.

[18] C. Nuttal. Smartphone rivals square up. *Financial Times*, 24 June 2010.

[19] A. Campbell, S. Eisenman, N. Lane, E. Miluzzo, R. Peterson, H. Lu, X. Zheng, M. Musolesi, K. Fodor, and G. Ahn. The rise of people-centric sensing. *IEEE Internet Computing Special Issue on Mesh Networks*, June-July 2008.

[20] MetroSense Project. http://metrosense.cs.dartmouth.edu.

[21] Urban Sensing. http://urban.cens.ucla.edu.

[22] N. Lane, E. Miluzzo, H. Lu, D. Peebles, T. Choudury, and A. Campbell. Mobile Phone Sensing: A Disruptive Technology for the App Phone Age. In *IEEE Communications Magazine*, September 2010.

[23] M. Srivastava, M. Hansen, J. Burke, A. Parker, S. Reddy, G. Saurabh, T. Schmid, K. Chang, M. Allman, V. Paxson, and D. Estrin. Network system challenges in selective sharing and verification for personal, social, and urban-scale sensing applications. In *Fifth Workshop on Hot Topics in Networks (HotNets-V)*, Irvine, CA, USA, November 2006.

[24] N. Lane, S. Eisenman, M. Musolesi, E. Miluzzo, and A. Campbell. Urban Sensing Systems: Opportunistic or Participatory? In *Ninth Workshop on Mobile Computing Systems and Applications (HotMobile'08)*, Napa Valley, CA, USA, February 2008.

[25] S. Eisenman, N. Lane, and A. Campbell. Techniques for Improving Opportunistic Sensor Networking Performance. In *International Conference on Distributed Computing in Sensor Systems (DCOSS'08)*, Santorini, Greece, June 2008.

[26] C. Boldrini and A. Passarella. HCMM: Modelling spatial and temporal properties of human mobility driven by users social relationships. *Elsevier Computer Communications*, 2010.

[27] A. Chaintreau, P. Hui, J. Crowcroft, C. Diot, R. Gass, and J. Scott. Impact of Human Mobility on Opportunistic Forwarding Algorithms. *IEEE Transactions on Mobile Computing*, 6(6):606–620, June 2007.

[28] H. Nguyen and S. Giordano. Spatiotemporal Routing Algorithm in Opportunistic Networks. In *2nd International IEEE WoWMoM Workshop on Autonomic and Opportunistic Communication (AOC'08)*, Newport Beach, CA, USA, June 2008.

[29] W. Jones. STMicroelectronics Makes 3-Axis Digital Gyroscope With One Sensor. *IEEE Spectrum*, March 2010.

[30] W. Jones. A Compass in Every Smartphone. *IEEE Spectrum*, February 2010.

[31] J. Flinn, D. Narayanan, and M. Satyanarayanan. Self-Tuned Remote Execution for Pervasive Computing. In *8th Workshop on Hot Topics in Operating Systems (HotOS VIII)*, Elmau/Oberbayern, Germany, May 2001.

[32] M. Satyanarayanan. Pervasive computing: Vision and challenges. *IEEE Personal Communications Magazine*, 8(4):10–17, 2002.

[33] B. Chun and P. Maniatis. Augmented Smart Phone Applications Through Clone Cloud Execution. In *12th Workshop on Hot Topics in Operating Systems (HotOS XII)*, Monte Veritá, Switzerland, May 2009.

[34] A. Miettinen and J. Nurminen. Energy efficiency of mobile clients in cloud computing. In *2nd USENIX Workshop on Topics in Cloud Computing (HotCloud'10)*, Boston, MA, USA, June 2010.

[35] H. Lu, W. Pan, N. Lane, T. Choudhury, and A. Campbell. SoundSense: Scalable Sound Sensing for People-Centric Applications on Mobile Phones. In *7th Annual International Conference on Mobile Systems, Applications and Services (MobiSys'09)*, Krakow, Poland, June 2009.

[36] B. Priyantha, D. Lymberopoulos, and J. Liu. Enabling energy efficient continuous sensing on mobile phones with littlerock. In *9th ACM/IEEE International Conference on Information Processing in Sensor Networks (IPSN'10)*, pages 420–421, 2010.

[37] M. Satyanarayanan, P. Bahl, R. Caceres, and N. Davies. The Case for VM-Based Cloudlets in Mobile Computing. *IEEE Pervasive Computing*, 8(4):14–23, 2004.

[38] A. Balasubramanian, R. Mahajan, and A. Venkataramani. Augmenting Mobile 3G Using WiFi. In *5th Annual International Conference on Mobile Systems, Applications and Services (MobiSys'10)*, San Francisco, CA, USA, June 2010.
[39] E. Cuervo, A. Balasubramanian, D. Cho, A. Wolman, S. Saroiu, R. Chandra, and P. Bahl. MAUI: Making Smartphones Last Longer with Code Offload. In *MobiSys'10*, San Francisco, CA, USA, June 2010.
[40] M. Conti and M. Kumar. Opportunities in Opportunistic Computing. *IEEE Computer*, pages 42–50, January 2010.
[41] M. Conti, S. Giordano, M. May, and A. Passarella. From Opportunistic Networks to Opportunistic Computing. In *IEEE Communications Magazine*.
[42] G. Shen, Y. Li, and Y. Zhang. MobiUS: Enable Together-Viewing Video Experience across Two Mobile Devices. In *5th Annual International Conference on Mobile Systems, Applications and Services (MobiSys'07)*, San Juan, Puerto Rico, June 2007.
[43] L. Pelusi, A. Passarella, and M. Conti. Opportunistic Networking: Data Forwarding in Disconnected Mobile Ad Hoc Networks. In *IEEE Communications Magazine*, November 2006.
[44] Haggle Project. http://www.haggleproject.org.
[45] ANA Project. http://www.ana-project.org.
[46] SCAMPI Project. http://www.ict-scampi.eu.