



Customized Services over Virtual Wireless Networks: The Path towards Networks without Borders

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Abstract: We propose a new architecture to enable wireless networks to meet the challenges of ever-increasing demand for high data rate services and ubiquitous connectivity, heterogeneity of access technologies, and spectrum scarcity. This architecture, which we call Networks without Borders, envisions a pool of resources (spectrum, infrastructure, network management, authentication, subscriber tracking services, etc.) from which a virtual wireless network can be orchestrated and instantiated. Flexibility and technology neutrality are key goals of this architecture, mirroring the Internet, where user services are independent of the underlying network control mechanisms or infrastructure. We outline some of the major trends in networking research and commercial deployments that provide an evolutionary path towards Networks without Borders. These trends include virtualization, reliance on small cells, dynamic spectrum sharing, crowdsourcing of wireless access, and inter-mobile operator resource sharing.

Keywords: mobile networks, virtualization, resource sharing, dynamic spectrum access.

1. Introduction

We envision the on-demand provisioning of wireless networks, virtualized over shared infrastructure, management and control services, and spectrum. This paper outlines an evolutionary path from current wireless networks to this new paradigm, which we call Networks without Borders (NwoB).

Our vision of future wireless network architectures builds upon advances on research topics that have focused the attention of the networking and wireless communications research community over the last decade. These topics include cognitive radio, virtualization, and future network architectures (each of which, not coincidentally, also a major focus area by funding agencies worldwide). Our proposed architecture recognizes the pressures on wireless providers to substantially increase their ability to support mobile data, while simultaneously keeping costs to customers fairly constant – pointing to the need for a new, sustainable business model that involves major changes in the way networks are provisioned. Finally, it seeks to harness the trend in telecommunications regulation towards more flexible modes of spectrum allocation and licensing. We believe that all these efforts lead naturally to more transient ownership of wireless resources and the ability to instantiate wireless networks dynamically, in response to dynamic changes in demand and customized to specific service requirements.

We believe our architecture follows naturally from recent trends in wireless networks, including:

- *Virtualization* – in the context of backbone wired networks, recent work on software defined networking supports increased virtualization of network resources by decoupling the control and data planes. Some progress has also been made in the virtualization of the air interface in mobile networks (e.g., [1] looks at virtualization in the context of LTE networks). Our architecture takes advantage of virtualization to dynamically customize a wireless network for the particular quality of service, demand, and coverage requirements of the service provider.
- *Small cells* – the spatial frequency reuse enabled by small cells is critical to meet the demand for high data rate wireless and mobile services. NwoBs rely on both wide area access and small cells, the latter of which can be either operator- or end user-deployed. Recent developments in standards to support mobility across WiFi networks and seamless integration between 3GPP and WiFi networks are critical to enable dynamic coalitions formed by networks that make use of diverse wireless access technologies.
- *Dynamic spectrum access* – the push for more flexible exploitation of electromagnetic spectrum was prompted by studies that show that current modes of spectrum licensing have resulted in inefficient use. The refarming of spectrum formerly allocated to analog TV broadcasting presented the opportunity to experiment with sharing etiquettes, and regulators are considering spectrum sharing for other frequency bands as well, such as bands used for terrestrial and maritime radar. Technology-neutral licensing regimes could also allow more flexibility in the use of cellular-band bands, as well as greater inter-operator spectrum sharing. In NwoBs, dynamic access to spectrum is key to dynamically orchestrate a virtual network.
- *Crowdsourcing the wireless access* – end users and small businesses have deployed extensive wireless access infrastructure, primarily in the form of WiFi access points. In most developed countries, WiFi penetration is in excess of half of all households (South Korea currently tops the list, with 80% of households having deployed WiFi). NwoBs seek to harness this infrastructure as a component of a unified virtual network, in what we call the crowdsourcing of the wireless access. This idea has a parallel in the concept of the smart energy grid, with end users opening up access to their wireless network to subscribers to the virtual network, and being compensated for it.
- *Inter-operator resource sharing* – this already happens, in the form of roaming agreements, co-located base stations, and leasing of services among operators. NwoBs accelerate this trend, with the dynamic aggregation of resources belonging to multiple operators to form a virtual network on the fly.

More than anything, this paper seeks to start a conversation about what wireless networks should and will look like in the medium-term future, and how to get there. We start by summarizing the Networks without Borders concept. In the subsequent subsections, we detail how each of the trends above sets a path from current networks to NwoBs. The final section of the paper is devoted to issues that need to be addressed for the architecture we propose to become reality.

2. Networks without Borders

Currently, the provider of wireless access services typically owns the infrastructure. For mobile networks, this means a cellular provider, which holds a license to the spectrum it operates on, owns the hardware and software for the radio access network (RAN), has long-term leases for backhaul and core connectivity, and operates its own support services for mobility management, subscriber tracking, billing, etc. Large commercial WiFi hotspot operators, such as Boingo, iPass, and Easy WiFi, similarly own the radio access

infrastructure, and lease backhaul connectivity to the Internet, typically through coaxial cable, DSL, and, increasingly, fiber. At a smaller scale, businesses, university campuses, and households also operate WiFi networks, sometimes comprising hundreds of access points, to support their own users. Figure 1 depicts the infrastructure and services owned and operated by current wireless network providers. Many of these lines are blurring. For example, mobile network operators (MNOs) increasingly rely on WiFi offloading to support the demand for high data rate services and deploy their own WiFi networks for that purpose. Conversely, commercial WiFi hotspot operators have their own management and control infrastructure for authentication and billing, for instance relying on captive portals.

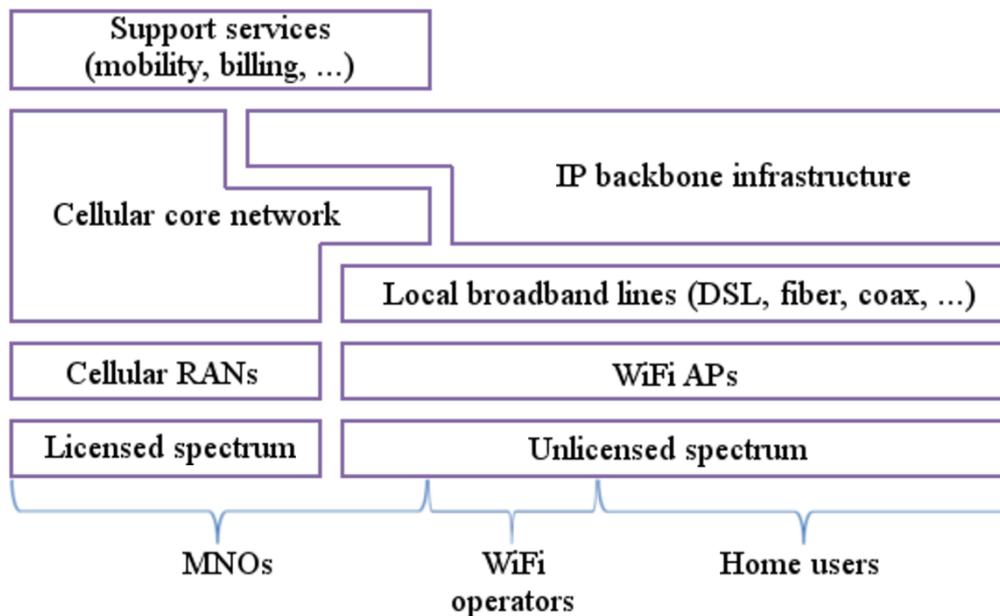


Figure 1: Infrastructure and services owned by current wireless network operators.

However, even today not all mobile operators rely solely on infrastructure and spectrum owned by them. In particular, a certain level of virtualization already exists in commercial services, in the form of Mobile Virtual Network Operators (MVNOs). MVNOs do not hold spectrum licenses nor operate their own RAN. Yet, a full MVNO may handle everything from the marketing of the service to customer care and billing, and the fact that the MVNO does not own its own radio access infrastructure is often transparent to the subscriber [2].

Our proposed Networks without Borders architecture goes a step further than current MVNOs. It customizes a virtual wireless network by combining, on the fly and to meet the needs of a service provider, resources from a variety of different entities. The principles are summarized in Figure 2.

The end user subscribes to one or more services offered by the (virtual) network provider, for instance a social network operator, or a video-on-demand service. As part of our concept some of these services will be bundled with wireless access, which will be provided and controlled by the service provider, which in turn makes use of the services of a Virtual Operator. The Virtual Operator interacts with one or more virtual network architects and network aggregators to determine the appropriate set of resources in the network that will yield the desired coverage and capacity for the network, and that will best meet the needs of the end user and the service. Virtual network architects and network aggregators operate on the virtualized resources owned by different infrastructure providers. These resources may be of heterogeneous nature and ownership, including but not limited to assets in the current mobile networks, household access points, cloud-based services, and frequency spectrum. Each role in the architecture may be played by one or

more entities in the newly formed wireless services market, and a single entity may function with more than one role.

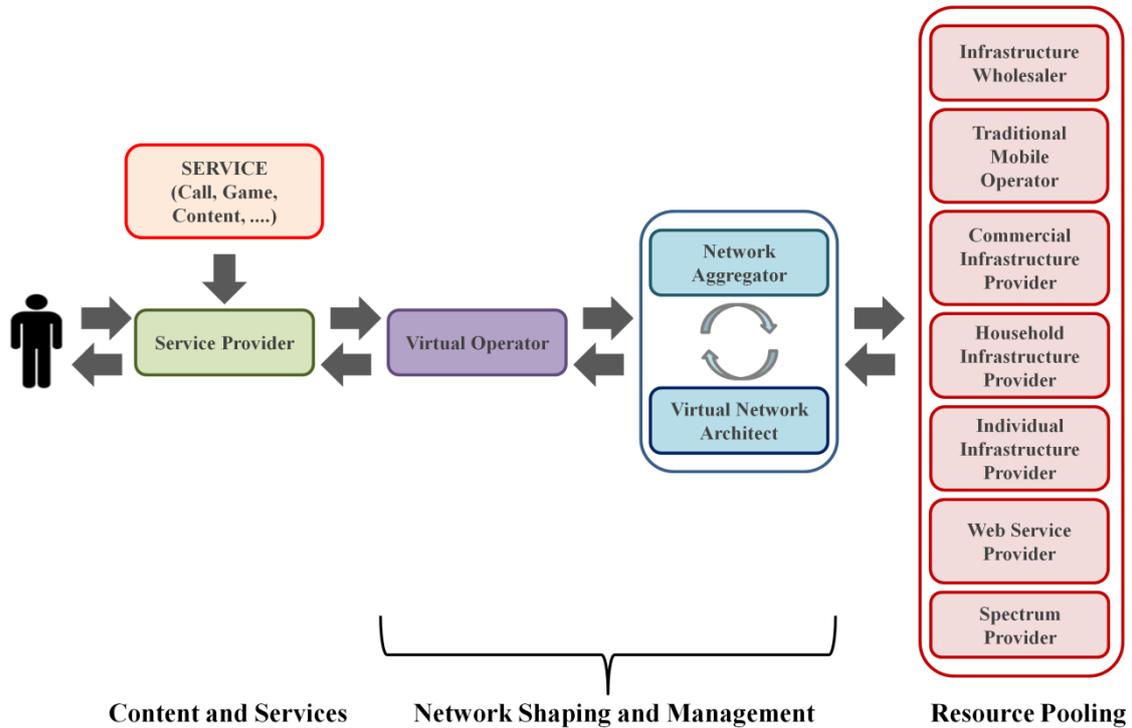


Figure 2: Networks without Borders concept.

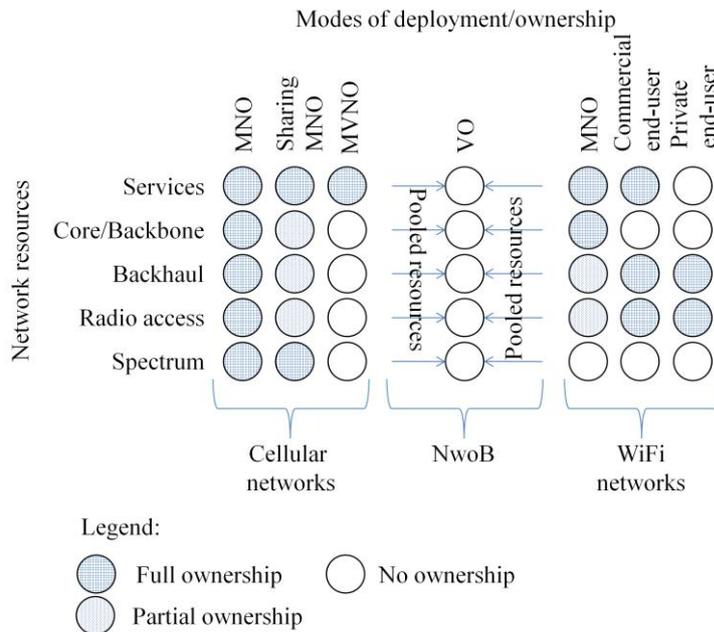


Figure 3: Resource ownership in Networks without Borders. Sharing MNOs refer to MNOs that own spectrum licenses and infrastructure but share some of these resources, e.g. through co-located base stations. WiFi networks can be operated by households (referred to as end-users), businesses, and MNOs.

The NwoB architecture [3] virtualizes many of the complex processes and functions that underlay current cellular networks, from network management to mobility management and authentication. These processes and functions are viewed as services, which can be traded among different parties to orchestrate a virtual network customized to the particular needs of a service provider. As a part of this vision the physical radio access infrastructure becomes primarily a transport mean for bits (packets), or otherwise an inter-connection point to the cloud of services. Similarly, the backhaul is another service provided in the composition of the virtual network. The resource picture becomes the one in Figure 3.

3. Key Enabling Trends

We now discuss how major recent networking trends provide the foundation for the evolution towards a Network without Borders.

3.1 - Virtualization

Virtual networks are subsets of the underlying physical network infrastructure, decoupling the service providers from infrastructure operators [4]. Shared resources (links, routers, channels) are allocated such that the virtual network appears to have exclusive use of these resources. Such networks have been widely adopted in commercial settings, from Virtual Private Networks to overlay networks.

In the NwoB concept, a service provider (e.g., a social network operator) would be unlikely to have the expertise or desire to dimension the network and negotiate the use of resources with a wide variety of players, from traditional operators of cellular infrastructure to existing and new businesses that provide access to WLANs, mobility management and billing, etc. For that purpose, we introduce a new role, of the virtual network architect, responsible for customizing the virtual network according to the requirements of the service provider and managing service level agreements with all infrastructure providers.

Virtualization of wireless networks comes with its own set of challenges, due to their operation in a medium that is inherently shared. In the research arena, the GENI program in the US relies on virtualization to explore new network architectures, slicing the network resources in space and time. This requires support for independent experiments to run concurrently while sharing a common set of devices and frequency bands. The approaches to achieve virtualization in GENI wireless experiments (e.g., [5]) provide a path to experiments on virtualization in other large wireless testbeds, and may eventually evolve to support the large scale virtualization and resource aggregation we envision in NwoBs. With a similar motivation but focusing on switching and routing elements within the network, OpenFlow [6] provides a solution to run networking experiments in the production network deployed in research labs and universities, again achieving resource virtualization. The ability to run large-scale testbed experiments is crucial to advance research on new wireless network architectures such as NwoBs, and we expect initiatives such as GENI and the testbed federations deployed under the European Commission's Future Internet Research and Experimentation (FIRE) program to be important assets in this work.

3.2 – Small cells

The path to high capacity mobile networks will certainly include small cells. This is a continuation of a decades-long trend, as increasing spatial frequency reuse has been the primary factor responsible for the impressive gains in aggregate capacity from the early days of cellular networks to today's 4G. The term *small cells* serves as a large umbrella that encompasses many distinct solutions, from the re-planning of existing cellular networks

with greater reliance on micro- and pico-cells, to user-deployed femtocells, to WiFi offloading and up-and-coming technologies such as mm-wave communication systems.

Femtocells are already deployed in several countries – they are end-user-deployed and tied to a particular operator and 3G or 4G services. To date, they have been primarily useful in providing indoor coverage to customers experiencing dead spots, in particular in support of voice traffic. There is significant research on interference management for femtocells, as well as proposals that specific spectrum be allocated to support these femtocells, at higher frequencies. To date, however, WiFi has been the most critical subscriber-deployed technology to support wireless data traffic from smartphones, tablets, and laptops/desktops.

For several years now, solutions have been proposed to make roaming across disparate access technologies, such as 3G/4G and WiFi, more seamless (e.g., [7]). Mobility management in support of roaming across heterogeneous networks was also considered by [8], who qualitatively compares mobility management solutions at various layers of the protocol stack, assuming an all-IP wireless network. The need for such solutions becomes more pressing as cellular operators increasingly rely on extending their own networks with local WiFi deployments. A recent IEEE standard tackles the issue of providing handover between different radio access technologies (RATs), and there is progress in allowing non-3GPP access networks to access to the 3GPP Evolved Packet Core.

The IEEE 802.21 standard, on media-independent handover service, seeks to optimize heterogeneous handovers, including technologies that are part of the 3GPP and IEEE 802 standardization efforts. One main objective is to enable more efficient handover decision processes, including candidate network discovery, network selection, and the control of handover timing and initiation [9] [10].

Authentication is another challenging area for heterogeneous handover. The delays and overhead involved in authenticating with multiple networks managed by different operators may be significant. Dutta *et al.* [11] propose a pre-authentication solution for the mobile to obtain an IP address and other configuration parameters for the visited network but can also start exchanging packets using that IP address before attaching to the network.

Roaming support functions such as authentication and mobility management are crucial to sharing of service infrastructure among providers and may eventually enable a completely virtualized wireless network built on top of infrastructure deployed by multiple operators.

3.3 – Dynamic Spectrum Access

Numerous studies have concluded that spectrum, although fully allocated, is sparsely used. The natural question, then, becomes whether regulators can adopt more flexible modes of spectrum licensing that will lead to greater efficiency in spectrum use without compromising the level of service provided by incumbents, ranging from broadcasters to commercial operators to military and other government agencies. While the question is far from settled, it has ignited a flurry of research on dynamic spectrum access and cognitive radio and has led to some regulatory changes, in particular in bands currently or recently occupied by TV broadcasters.

The added flexibility in spectrum access regimes may end up taking different forms. The one that has received the most attention is opportunistic use of spectrum on a non-interfering basis, aided by geolocation databases. Other possibilities include short-term leasing of spectrum, perhaps coordinated through a spectrum broker, and spectrum trading and sharing by current license holders.

All of these allow us to think of spectrum as a resource that can be allocated dynamically in support of the Networks without Borders that we envision. Dynamic access

would also allow the aggregation of spectrum bands with exclusive access, secondary access, and unlicensed access (such as the current ISM bands).

On the theoretical front, we have used game theory to analyse incentive structures for spectrum license holders to lease spectrum to secondary users. We first formulate a coalition formation game to study sub-band allocation among secondary users and then integrate the coalition formation game into a hierarchical framework, whereby incumbent license holders dynamically lease spectrum to secondary users [12]. We prove that, if the pricing coefficients of licensed holders have a fixed linear relationship, the sub-band allocation of secondary users will be stable and the Stackelberg equilibrium of the hierarchical game framework will be unique and optimal. We have proposed a simple distributed algorithm to achieve the Stackelberg equilibrium of the hierarchical game [13].

3.4 – Crowdsourcing the Wireless Access

A core part of our vision is that networks of the future will be composed from a pool of infrastructure that comes not just from traditional mobile operators but also contains crowdsourced elements. In line with this belief a body of our current work focuses on the building of networks from the bottom-up in a manner that allows independent service providers, small or large, to form loose coalitions that support user mobility from one service provider to the other. This is in contrast to the top-down tight control we see in mobile networks today.

One solution we have been exploring builds on early work in the area of cyclostationary signatures [14]. The signature acts both as a means of identifying the coalition and of supporting handover between service providers. Crucially, the approach does not require each service provider to use static assignments of spectrum – instead, each service provider can dynamically obtain spectrum from wherever it is available and the service provider and users can reconfigure as the spectrum in use changes. We have validated some of these ideas experimentally on the CREW testbed federation [15]. CREW is a pan-European FP7 project that provides experimental facilities for cognitive radio exploration.

We continue to investigate incentive structures for operators of all sizes (cellular operators, operators of WiFi networks, households) to cooperate in providing wireless connectivity.

3.5 – Inter-operator resource sharing

Mobile operators have been sharing resources for a long time, through roaming agreements. The NwoB architecture calls for even greater sharing, on behalf of a customized virtual network that is not fully controlled by any of the participating infrastructure providers.

To illustrate the potential for infrastructure sharing among operators, we conduct a preliminary case study based on the Polish mobile market. We have selected Poland for the maturity of the market and the availability of the data. Mobile market penetration is 131% (corresponding to 51 million active SIM cards), with the mobile network coverage exceeding 90%. The service usage by a single active user is close to the European average. By 2012 there were 7 infrastructure operators and 16 MVNOs, of which the four major infrastructure operators had 99% of the subscriber share and 99.7% of the market revenues [16].

In our case study we focus solely on network infrastructure sharing and base station sharing. We have selected four locations in Poland, which represent a mix of commercial and residential areas: Warszawa, Wrocław, Olsztyn, and Świdnica. We have extracted base station radio license information from Polish communications regulator UKE (available online at <http://btsearch.pl/>). Each snapshot we examined, e.g. Figure 3, comprises a 10.9 x

2.7 km² area, centered at the city centre, that contains base station sites coordinates for all four major Polish infrastructure operators (Orange, Play, Plus, T-Mobile), for three radio technologies: GSM900 (GSM operating in 900 MHz), GSM1800 (GSM operating in 1.8 GHz) and UMTS2100 (UMTS operating in 2.1 GHz). Table 1 summarizes extracted site information for each of the locations, whereby the most commercial location has an order of magnitude more sites than the third and fourth locations. Based on the extracted data we can assess the popularity of site co-location for the four locations. What we notice is that, while the intra-operator (inter-technology) co-location is at a reasonably large level, the inter-operator site co-location, which is not technologically demanding (but requires inter-operator agreement and coordination), is relatively infrequent.

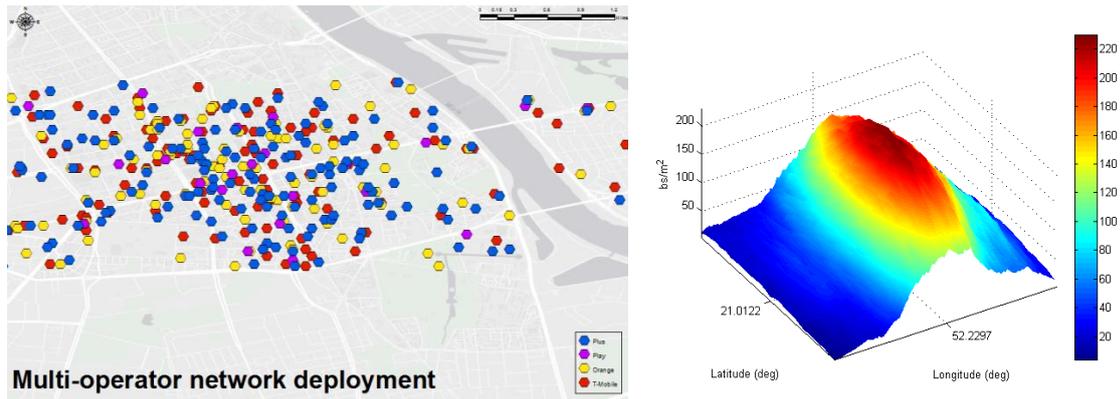


Figure 3- Warszawa multi-operator base station sites. On the left hand side we show base station placements for the four major operators. On the right hand side we show network density distribution (bs/m²) for the same area, excluding the top and bottom slices. As we can see the highest density of base station (i.e. the highest number of base stations that a mobile station can potentially attach to in a given area) is precisely in the Warszawa city centre.

Table 1 Information about extracted sites

Location	Number of cellular sites	Number GSM900 sites	Number of GSM1800 sites	Number of UMTS2100 sites	Percentage of intra-operator co-located sites	Percentage of inter-operator co-located sites
Warszawa	514	423	174	337	54.9	4.5
Wrocław	273	207	122	229	66.3	8.1
Olsztyn	74	56	37	68	79.7	5.4
Świdnica	29	27	13	20	65.5	6.9

In order to evaluate the network sharing potential for the four locations, we have simulated the coverage area of the cellular base stations (according to radio access technologies that correspond to the radio licenses available in the specific geo-location). Each base station transmits its signal at a power allocated according to one of two scenarios: 1) homogeneous, where all base stations are assigned omnidirectional macrocell coverage with an equivalent isotropic radiated power (EIRP) of 45 dBm; 2) heterogeneous, where base stations are assigned omnidirectional macro- or microcell coverage (allocated based on the inter-base station distance) with EIRP of 45 and 38 dBm, respectively. Each

cellular signal propagates over an environment that is modelled according to the modified Hata model [17].

One of the parameters that determine the sharing potential is the network density, which can be represented by the number of cellular base stations that are visible from a one square meter area (bs/m^2). In Table 2, we summarize the network density data for the densest location and the sparsest location. From this data, the probability density function of the network density appears to have a heavy tailed distribution. Data from both tables indicate that there is potential for customized virtual networks that aggregate resources from multiple operators, either to provide broader coverage than any of the current operators can offer at the moment or substantially higher data rate service in the areas of greater demand (or both).

Table 2 Statistical description of the network density (bs/m^2) for the locations with the highest density (Warszawa), and with the lowest density (Świdnica)

	Mean	Median	Maximum	Standard deviation
Homogeneous power allocation				
Warszawa	92.1	79	234	61.5
Świdnica	7.2	6	23	4.6
Heterogeneous power allocation				
Warszawa	54.7	47	153	35.1
Świdnica	4.1	3	18	3.4

A critical factor in determining the potential for inter-operator infrastructure sharing is the temporal correlation (or lack thereof) in the demand experienced by operators. We have started to characterize the distribution of traffic demand, both temporally and spatially, for rural and metropolitan areas in Ireland, using real data from Irish regulators and operators.

4. Conclusions

In this paper, we present a vision for the evolution of wireless networks, towards greater sharing, virtualization of resources, and harnessing of user-deployed wireless infrastructure. This evolutionary process has already begun, as mobile operators increasingly rely on small cells and WiFi offloading and regulatory bodies experiment with more flexible spectrum regimes. The crowdsourcing of wireless access, while still incipient, is also starting, with emerging businesses dedicated to architecting a large network out of WiFi access points deployed by small businesses and households.

Yet, technical, regulatory, and economic challenges remain to make these Networks without Borders a reality. Economic incentives are needed for infrastructure providers to continue to invest in infrastructure deployment management under this new architecture. We believe this architecture can lower barriers to entry for new service providers, but to this end we must more precisely articulate the roles of the various players involved in bringing together a virtual network out of resources controlled by multiple parties. We are heartened by current interest in collaborative consumption and the sharing economy, beyond the scope of telecommunications, as it may unlock some of the economic structures that will come to support NwoBs. To what extent wireless network resources are fungible will play an important role in modeling this economic scenario – the fungibility of spectrum is of particular interest here and has just begun to be studied [18].

On the technical side, we continue to work on developing radio resource management mechanisms that must consider how to select from a pool of resources belonging to multiple operators that currently offer some degree of overlapping coverage, seeking to meet a mix of aggregate capacity and individual QoS goals for the virtual network. We are also interested in the requirements that this new wireless network architecture poses to the

architecture of the optical access network for backhaul and inter-base station communication and coordination.

Acknowledgements

This material is based in part upon work supported by the European Commission under Framework Program 7 (FP7) project CREW, grant ICT-258301. It is also supported by the Science Foundation Ireland under grants no. 10/CE/I1853 and 10/IN.1/3007.

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