Urban Wireless Community Networks: Challenges and Solutions for Smart City Communications*

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ABSTRACT

Is a different (from the global Internet and Cellular Networks) model for urban communications and networking conceivable? Can Community Networks, now flourishing in many parts of Europe and the world, be the next *'big thing'* in networking, for once considering the needs of people and urban evolution as a key element, and not as a side effect of technology or business? This paper discusses recent evolutions of Community Networks in Urban Areas, blending the technical analysis of their topology and evolution, together with grand challenges ahead and the need for a novel, transdisciplinary science that can guide the design of the future communication space for smart cities and beyond.

Categories and Subject Descriptors

C.2.1 [**NETWORKS**]: Network Architecture and Design—*Distributed networks; Wireless communication*

Keywords

Wireless Community Networks; Smart Urban Environments; Crowd Design; Participatory Networking: Societal Changes; Law Influence

1. INTRODUCTION

This paper starts posing a question: Is the Internet the only communication model possible? The follow up is a discussion of one possible alternative, or better complement, to the Internet and cellular networks: Urban Wireless Community Networks (UWCNs). We stress the *urban* dimension not because Wireless Community Networks (WCNs) cannot flourish in rural environments, but because we think that inside cities they can grow to have a role which is not only an access network (to the Internet) or an instrument to reduce the digital divide (whatever this means), but they can sustain entirely novel communication paradigms that not only break the Telco and Internet Service Providers (ISPs) oligopoly in communications, but also shatter the much more subtler trust of information mediators and aggregators (search engines, centralized social networks, etc.) that are today controlling the way information flows around the world, as the "Snowden Affair" has recently brought to the general public attentions.

We also stress the complementarity of UWCN with respect to global networks like the Internet and cellular networks: They are not meant to replace them, nor to be a competitor, rather to offer different strategic alternatives for some services, as well as enablers of others, if they include also short range communications with handheld devices. This latter point can be the real enabler of a smarter living space, where services related to sociality, safety and intelligent mobility (to name a few) can find a technical and socially sustainable cradle.

2. URBAN WCNS

WCNs are surely not a novel idea; they flourished as soon as wireless LANs became available and legal [2, 3]. So why going back to twenty year old ideas and technology?

Indeed, technology has not frozen, and recent advances enable the conception of WCNs that open new possibilities. If these possibilities and opportunities are well exploited, and the legal framework does not jeopardize them, WCNs may become the fertile humus out of which we can grow services that will make inhabited environments smarter and more pleasant to live in.

Moreover, many of the distinguishing features of UWCNs are not strictly technical. Their intrinsic differences from other communication networks primarily rely on their cooperative, bottom-up nature. It is thus necessary to briefly review the reasons that are leading to the emergence of this new social networking model.

2.1 The global context

At the beginning of the World Wide Web (WWW) the client/server model shaped the communications and its application allowed the access to static information placed on web-servers. This changed with the advent of the so-called 'Web 2.0' that allowed people to be the source of the information with blogs and social networks. In this phase, it seemed that the WWW was taking the form of a peer-to-peer based system, exploiting the decentralization and neutrality that are at the base of the IP paradigm. In the last decade, instead, the the emergence of cloud systems lead to a re-centralization of the services. Today, a few major service providers control a very high percentage of the whole Internet information flow.

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The market of Internet access followed a similar path to centralization. In many countries a few ISPs control the majority of internet access. This often leads to a distortion of the market and disadvantages for the customers, testified by list of sanctions imposed by the European Commission on Telcos[1].

From a technical point of view, centralization is just an economic trend; from the social point of view, instead, it has severe consequences. We briefly review two of them, since they are at the base of the search for alternatives that lead to the new rise of UWCNs.

The first is embodied by the ongoing discussion about the neutrality of the access to the Internet (the debate on the "Net Neutrality"). The basic principle of TCP/IP is that the management of the information takes place at the end-points, and that the intermediate nodes will do their best to simply route all the data packets. Routers should be neutral, they should not give precedence to a packet over another based on the final destination, and they should not inspect packets' content. Net neutrality has been under attack almost forever, and today is again under discussion both in the EU and the USA. There are enormous interests in letting service providers pay a fee to ISPs to ensure that ISPs will prioritize their services compared to others. When this happens, as unfortunately happens regularly one way or the other, the nature itself of the Internet is jeopardized, and the final users are driven to use some services instead of others, finally killing the rise of alternative applications and communication models.

The second consequence is loss of privacy, the difficulty to protect users' data, even the most personal and sensitive. When the majority of the communications are managed by a few ISPs, and are terminated on a few service providers, it is easy to identify the critical points of the infrastructure that can be exploited to perform mass data collection of the users. Concentration has a consequence both on the technical feasibility and on the legal and social sustainability of data protection and management. If a few entities control the vast majority of the Internet traffic, fairly simple techniques are needed to collect, analyse and correlate private data. Accordingly, if a few service providers control the vast majority of users' interaction, it takes a few economical and legal arrangements to access the data of billions of users. This is what the recent "Datagate Scandal" has shown, and this is only the tip of the iceberg that has been seen by anyone: The large part of personal data leaks and misuse is surely well buried below the calm surface that we see.

Community-driven and bottom-up networks are collective efforts to give an answer to these problems. They started as a way to share the cost of Internet Connections, but evolved in something different. Understanding their social foundations and the legal provisions that can foster them is the key element to analyse their technical challenges and drive their evolution for the benefit of society. Indeed, today they appear, to the acute and farsighted observer, the only technically feasible and economically sustainable solution for the development of smart cities and other pervasive intelligent spaces without forgoing fundamental human rights as the right to be left alone, the right to control and retain personal sensitive data, the right to independent decision-making, the right to avoid being manipulated.

[1] `http://ec.europa.eu/competition/sectors/telecommunications/broadband_en.html`

2.2 Technology and local context

From the computer science perspective, Wireless Mesh Networks (WMNs) have been a lively field of research starting in the '90s. In the context we are considering, they have been conceived most of the times as a last-mile replacement, rather than a communication technology to enable a different model of communication between people. This view is the direct consequence of the evolution of the Internet we outlined before: Since the main reason to be on-line is to access the mainstream network services, then WMN have been primarily imagined as a way to access the Internet. Thus, there is a lot of research dealing with how to use WMN in rural areas, emergency situations, and other scenarios in which there is no other connectivity. WCNs made no exception in their early stages [11]. This point of view should be corrected, in light of recent developments carried out by some communities, where a WCN is a WMN created by a local group of users to have an alternative, self-managed, community based networking infrastructure.

WCNs are flourishing [1]. Many European cities feature WCNs with hundreds of nodes: in Athens a single WCN, AWMN includes more than 2,400 nodes, in Spain, the Guifi network is a composition of WCNs that counts more than 23,000 nodes and it is growing[2]. Thousands of nodes connecting tens of thousands of individuals, families, associations, public offices with a non-profit approach and a community-based organization. WCNs are no more a last-mile replacement: They are becoming a social phenomenon that reinforces community relations even in urban areas abundantly covered by commercial ISPs.

That's why we stress the *urban* nature of such networks, not because their deployment in rural environment is not important, but because we are mostly interested in their use when it is deeply intertwined with the social aspects of a true community. The users of UWCNs are not *forced* to use an alternative network, it is their choice to use it. Thus the community sets up internal services in the WCN that are independent from any Internet-based service, e-mail, web-hosting, VoIP, social networks, etc. They generally choose an organization that is horizontal, as it is typical of communities: The wireless mesh is technically de-centralized, the services are offered to peers and decision are taken by consensus. Most of the users feel part of an autonomous community that give them a partial independence from the mainstream service and connectivity providers.

These developments have recently re-attracted the attention of the academia that considers WCNs a stimulating open field to experiment innovative applications and protocols [5, 10, 14, 18]. The technological aspect is playing a major role here. High speed ($> 100\,\text{Mbit/s}$), medium distance (up tens of kilometers) links are simple to realize and computing/storage resources are cheap and abundant, but the 'networking' consequences and the tools to manage and deploy are lagging behind.

2.3 Going one step beyond: Mobility

So far, WCNs have been deployed on people's roofs, terraces and windows, and they generally do not support mobility. The users access the network resources from inside their homes. Nevertheless, support for mobility and inter-

[2] See `http://guifi.net` and `http://awmn.net` for further information

play with other community-based initiatives is the next step of their evolution. We can foresee at least three ways that the scientific community is exploring to go in this direction, with the last one the one we like the most.

The first is extending a WCN to a 'nomadic' context: the network is made available where users are, without mobility, handovers, or roaming. An example is "Nodo Movil")[3], which simply uses battery-powered mesh nodes to give connectivity outdoor. This is a simple extension of a WCN to an uncovered area: the outdoor installation can become permanent and cover places of interest for the community. This seems to be just a matter of management, legal framework (does offering connectivity in a public place make the WCN an ISP?) and sometimes of economic resources.

The second is proposed by the Serval project[4]. The idea is to use off-the-shelf products to build a mesh-infrastructure able to replace and integrate existing cellular networks. The prototype has been tested in a few occasions and has shown the feasibility of the concept of using direct mobile-to-mobile communications and a multi-hop mesh network integrated with GSM cellular networks. Very similar to this approach is the Open Source GSM networking as for instance the one in Telea de Castro in Mexico[5].

The third one takes a grander perspective, already discussed in [12]. Technologies are in the end only enablers, key evolutions come from ideas and lateral thinking. Short range wireless communications are a technology enabler, now we have to generate new ideas to empower a different communication model through UWCN, and this poses new grand challenges, as we discuss in Sect. 3. These challenges go far beyond the solution of some "problems". We have introduced users' management, multi-gateway support and novel Multi-Point Relay (MPR) selection methods in Optimized Link State Routing Protocol (OLSR) [8, 15], and changed address management and distribution in B.A.T.M.A.N. [17], but these will not transform a WCN into a UWCN.

WCNs have never attempted to exit from houses and go mobile because of social and legal concerns, not because smartphones and tablets cannot communicate directly between them or because they cannot connect to a WCN Access Point (AP). Remove these concerns and a new plethora of services will open up for UWCN. Location based services are today a threat to privacy because they are all based on the communication of user sensitive data (not only location) to centralized services that manipulate users' choices. A mobile device in a UWCN instead will be able to know its position not only based on GPS coordinates (kept local), but also on the surrounding UWCN APs, and the local services available can be simply located on the APs themselves. Some people claim that the density of APs is simply not enough, but a look at the few works as [4] that have really analysed the potential tells a different story.

Direct communications among mobile devices, once integrated into a UWCN, will empower many new services, including services improving the mobility in big clogged cities and increasing the safety of urban roads (just think about all the works dealing with early warning systems to avoid collisions in sub-urban crossroads). Integration in UWCN is essential to use APs as relays when needed, and to build devices' mutual trust, which in general requires some form of third party connectivity to verify the claims of the other device. This last point is very similar to the proposals coming from cellular operators under the WiFi Direct and LTE Direct proposed standards, but it is very difficult to conceive that novel services for the benefit of people will come from big operators unless the benefit is a side-effect of an economic benefit for the operator (offloading the cells in this case).

[3] `http://www.mobilitylab.net/nodomovil/`

[4] `http://www.servalproject.org/`

[5] `http://phys.org/news/2013-08-forgotten-telecoms-mexico-town-cell.html`

3. A NEW SCIENCE FOR UWCNS

So far we have discussed and analysed the concept of UWCN, some existing realization of UWCN, potential future developments. Now it is time to discuss if this all is worth the attention of the scientific community, i.e., to understand if UWCNs can be scientifically studied and designed, and if yes, how.

Network is a general term used within many different scientific areas, from sociology, to law, from transports, to hydrology, to communications and many others. For each of these communities the term bears a different meaning, but in general a graph $G(\mathcal{N}, \mathcal{L})$ is used for its description, with $\mathcal{N}$ being the set of entities composing the network and $\mathcal{L}$ the set of edges describing their relationship.

In no other field but communications, the term network has became in time so intertwined with it to be somewhat a synonym; and in no other field but communications, a simple graph $G(\mathcal{N}, \mathcal{L})$ is deeply insufficient to fully describe and represent the underlying network. Is $G(\mathcal{N}, \mathcal{L})$ describing logical links and IP routers? Or is it describing the underlying physical network? Or rather the societal network of people and entities that do communicate?

Communication networks have become so complex that we are very often short of technical terminology and tools for their sheer description, let alone analysis and design. In the last twenty years or so, communications have undergone a number of technological, societal and legal changes, which are starting to take their toll, and pose societal questions and challenges unthought-of just a few years ago.

The picture we made of UWCNs in Sect. 2.2 is strongly based on the societal drivers that lead to the realization of new bottom-up technologies. The innovation produced by these models is a new interpretation of technologies that twists the mainstream way of intending networking. Nevertheless good intentions are not enough. So, how can we design and build networks that follow a different communication and societal paradigm from the dominating one?

Technology in the end is only a tool, not the final driver for the evolution of systems and society. If we want to build future networks with a new societal impact we simply can not split the societal dimension from the technological one. So the real challenge is: can we consider in a unique vision the technological and societal aspects of a community network?

There is also a third dimension of the analysis we have not mentioned so far: Law and regulations, which play a key role in this scenario. To analyse the complex interactions between these different disciplines a *'new science'* is needed. Being computer scientists, we claim that science means quantitative analysis and the ability to design systems and to predict what the outcome of the design will be. And this is a formidable challenge when a trans-disciplinary approach across communications, a bit of computing, sociology, and law is taken, but this is the unknown path to explore if we want citizens to be able to shape their urban communication environment, and do it with acceptable social and economic costs.

In the following we discuss some possible formalisms and tools that can be applied to capture the trans-disciplinary nature of UWCNs and to embed their different dimensions into the unitary framework of design and analysis.

3.1 UWCNs as Graphs

Graph theory has been widely used in sociology and communications, less in law studies. Considering a UWCN is thus rather natural to represent its different dimensions with graphs: $G_s(\mathcal{N}_s, \mathcal{L}_s)$ for the social network, $G_l(\mathcal{N}_l, \mathcal{L}_l)$ for the legal support, $G_c(\mathcal{N}_c, \mathcal{L}_c)$ for the communication network it defines. Is this sufficient to represent, analyse and design a UWCN? No! Definitely not, because it fails to grab the trans-disciplinary relationships.

$\mathcal{N}_s$, $\mathcal{L}_s$, $\mathcal{N}_l$, $\mathcal{L}_l$, $\mathcal{N}_c$, and $\mathcal{L}_c$ are all separate and independent sets in this representation, thus the three graphs defined above fail to grab, e.g., the impact of social interactions on communications, or the consequences that a different legal framework has on the society and thus on the development of the communication network. What we need is a multi-dimensional graph representation, where each dimension refers to one discipline, but trans-disciplinary implications are grabbed by links that connect nodes across different dimensions. The formal representation of this graph is easy, as it is sufficient to add a $d \times d$ matrix $\mathbf{W}$ of "weights" to each link. d is the number of disciplines that we want to model and that are represented as different dimensions of the graph. $\mathbf{W}$ components represent the relationship between nodes connected by a link in the d dimensions of the problem. We have d^2 components because each discipline can potentially influence all others. In our example, where a network involve the disciplines of communications, sociology and law, if two nodes i and j are connected by link l_{ij}, the link will be associated with the matrix $\mathbf{W}_{i,j}$ that describe the nodes' relationships. Some components of the matrix can obviously be void.

The term weight is used here with a very generic mean, because the relation, say, between the social dimension of a node and the legal dimension of another node can be an arbitrary set of attributes. Thus a UWCN can be represented as a graph $G(\mathcal{N}, \mathcal{L}, \mathcal{W})$ interconnecting all the nodes in a single, correlated, multi-dimensional relationship. $\mathcal{W}$ is the set of all matrices $\mathbf{W}_{i,j}$ that are associated to the links l_{ij} when they exist. Nodes in this representation are no more the usual nodes of graphs $G_c(\mathcal{N}_c, \mathcal{L}_c)$, $G_s(\mathcal{N}_s, \mathcal{L}_s)$, or $G_l(\mathcal{N}_l, \mathcal{L}_l)$, because a node in this multi-dimensional representation is not a simple piece of electronics (as in $G_c(\mathcal{N}_c, \mathcal{L}_c)$) or a person (as in $G_s(\mathcal{N}_s, \mathcal{L}_s)$), but they are abstract representations that may include a router or a person or a legal entity, but are none of them.

Fig. 1 gives a visual support to the different representation. The left hand side shows the different graphs identifying the relations between nodes in different dimension, which are not able to grab the inter-dimensional relations, which instead exist in the real world that is intrinsically trans-disciplinary. The right hand side gives a multi-dimensional representation; here, the links are multidimensional and described by the $\mathbf{W}_{i,j}$ matrices.

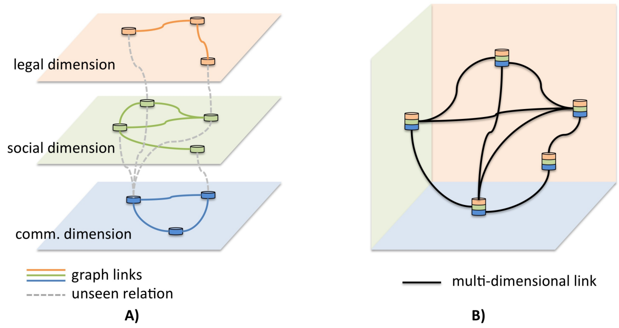

Figure 1: **A)** multiple graphs in separate dimensions, and **B)** Single multi-dimensional graph

The formalization of the problem seems easy, but apply it and gain insight in the problem is a formidable task. Some partial attempts can be found in papers like [13, 16], which address partial problems like introducing the concept of multidimensionality or including stochastic descriptions. This latter point points to another technique that can be combined with multi-dimensional graphs to increase the descriptive power, but also enhance the insight that can be given on the problem: Stochastic Graphs. We have successfully used Stochastic Graphs to describe the evolution of P2P systems (see [6, 7]) and design better P2P protocols. Applying the technique of Stochastic Graphs to multidimensional $G(\mathcal{N}, \mathcal{L}, \mathcal{W})$ graphs is particularly challenging.

3.2 Graph Semantic

Social relations are not only difficult to quantify, but also to identify. Sometimes finding social links and relations that are not the consequence of a direct communication between the social nodes escapes simple analysis. The literature on social networks is huge, and recently we have observed an area of convergence between sociology and computer science, with the use of advanced artificial intelligence techniques to analyze social networks. We have recently used untrained Support Vector Machines (SVMs) techniques in the analysis of the social behavior of the telephone network in our institution, discovering behaviors and relations unknown before, and also impossible to highlight otherwise [9].

The inclusion of legal aspects into the design process of a network has always proven very difficult. Law does not use a mathematical language, and it has been traditionally impervious to any quantitative approach. Computer science, however, has in the past thirty years made enormous steps toward the quantitative analysis of traditionally non-scientific fields, like semantic analysis and natural language processing. Consider, for instance, ontologies, that we used to link the legal and computer science domains in the Discreet project[6] in the context of privacy protection in pervasive environments. This is however just one of the many possible approaches, one we are aware of.

On the other hand we observe that technologies support the organization of communities in a very practical way. There exist several free, open source platforms to manage projects, group communication, decision making, fund-raising and many other activities that are typical of large communi-

[6] http://www.ist-discreet.org/

ties. People use these platform to accomplish their societal goals efficiently, and at the same time they leave a trace that can be automatically analysed with software tools. Such an analysis is used to identify social relationships (and leaders) in an established body of literature. We claim it can be used to help identifying also the responsibility dependency among the people, and this can be used to shape the graph representation of the legal dimension. For sure we completely miss instruments to analyse the complex interactions of the three layers, but this is the challenge of a *new science*. Once these instruments will be available, it will be possible to analyse the complex multi-dimensional graph that represents an UWCN and find and fix failures spanning across all the involved dimensions.

The discussion on tools for the description and analysis of the social and legal dimensions of UWCNs would still be very long, but we have to come to a closure, and opening new sciences is not (normally) a matter a single paper.

4. THE ROAD AHEAD

What lies before us in the evolution of digital communications? Drawing a conclusion would be preposterous on the one hand and arrogantly chesty on the other hand.

What we like to think we will see in the future is an epoch where people re-appropriate their own communication spaces, bending technology to the needs of society, and where legal provisions help moulding society for the benefit of the majority, and not for the economic advantage of the few. UWCNs are one possible tool to implement this future that we hope will not be an utopia; however, WCNs as we know them today are not enough, as they suffer from many limitations and drawbacks, which are not rooted in technology, but in the lack of a broader science that enables the full understanding of communication networks, a science that encompasses different dimensions and includes in a single coherent framework the computer science realm, the societal realm, and the legal realm that influence the evolution of such complex systems. We have called *urban* this possible evolution toward a novel communication paradigm centered more around people needs than around economic benefits.

Thus, the scientific road ahead is a complex path of understanding at the same time technology, societal changes, the influence of legal decisions on the evolution of complex systems. To reach this goal we need better conceptual tools that spans across scientific domains that have remained for decades quite impervious one another. We need tools that will be able to guide communities and designers in their choices and decisions, knowing in advance the consequences of their implementation and acts, thus avoiding the stagnation of fearful non-decision that we often see in face of the unknown global consequences the follow one's local choices.

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