Capillary Networks:
A Novel Networking Paradigm for Urban Environments

Isabelle Augé-Blum, Khaled Boussetta[*] , Hervé Rivano[†]
Razvan Stanica, and Fabrice Valois
Université de Lyon, Inria, INSA-Lyon, CITI – F-69621, Villeurbanne, France
Herve.Rivano@inria.fr

ABSTRACT

In this paper, we present our vision of the networking challenges induced by the rise of Smart Cities. Smart Cities leverage massive data collected by sensors, connected devices, social applications, etc. for proving a whole set of new services to the citizens. We identify the emerging needs of Smart Cities, focus on the *capillary networks* paradigm which unifies the wealth of wireless connectivity available in urban environment, and present the research issues it yields.

Categories and Subject Descriptors

C.2.1 [**Computer-Communication Networks**]: Network Architecture and Design—*Wireless communication*

Keywords

Urban networks, capillary networks, sensor, mesh, vehicular, real-time networking, Smart Cities, Digital Cities

1. SMART CITIES PARADIGM

The rapid growth of the cities yields new challenges spanning from the social to the technical point of view. Because the world becomes more and more urban [1], because the population density exceeds more than 5'000 inhabitants per km^2, as the life today requires to be always connected to social networks, and as natural resources like electricity, gas or water need to be carefully managed, traditional management processes, services and entertainment should be redefined.

The concepts of Digital and Smart Cities are being constantly refined and expanded to describe the future of major developed cities in a world where a large majority of people live in urban areas. Many actors are innovating, exploiting ICT for improving our cities sustainability, efficiency and quality of life, as illustrated by the 2010 universal exposition in Shanghai "*Better City, Better Life*" [2][1]

ICT are enabling an evolution from the duality between the "*real world*" and its digitalized counterpart to a continuum in which digital contents and applications are seamlessly interacting with classical infrastructure and services. The general philosophy of Smart Cities [3, 4, 5] is a paradigm shift combining Internet of Things and Machine to Machine infrastructures with a User - or Citizen - Centric model, all together leveraging massive data collected by sensors, connected devices, social applications, etc.

Institutions, including European Union [6] and NSF, therefore foster public initiatives, industrial development as well as research on finding breakthrough technologies for automatic and efficient management of energy networks, e.g. smart grids, regulated and sustainable mobility, real-time democracy and transparent government, added-value and growth enabling services, etc.

The first trends and output of these developments highlight a crucial need that might become a fatal bottleneck. Data gathering and disseminating are fundamental mechanisms of smart services and infrastructures which stresses the need for efficient, city-wide and manifold communication networks. Indeed, the density and mobility of potential data sources (sensors and user devices) as well as the dynamics of information destinations (control center, actuators, smart urban furnitures, or end user applications), makes it impossible to rely solely on wired, optical or even power line carrier technologies, or on access and metropolitan area networks. Unfortunately, even though developed cities can rely on a full coverage of their territory with very high throughput wireless access networks, the expected - and already measured - tremendous growth of mobile data traffic will overwhelm these infrastructures without a dramatic change of communication paradigm [7].

Beyond cellular networks, multi hop wireless mobile networks have been extensively studied in the literature, in particular wireless sensor networks, *ad hoc* networks, wireless mesh networks and vehicular networks. Such wireless multi-hop solutions met scarce practical success over the last decade, mainly because of the lack of a clear application context and of important use cases. There are however now mature technologies for some specific applications and provide a wealth of connectivity surrounding mobile devices. These manifold networking interfaces define a new class of

---

[*] Dr. Boussetta is Assistant Professor at Paris XIII University, on an Inria temporary position.

[†] Head of Inria Urbanet team `http://www.citi-lab.fr/team/urbanet`

[1] F. Valois was the organizer of a workshop on "*Digital Society for e-Human*" held at the French pavilion of the universal exposition : `http://expo-shanghai.insa-lyon.fr/`

Permission to make digital or hard copies of all or part of this work for personal or classroom use is granted without fee provided that copies are not made or distributed for profit or commercial advantage and that copies bear this notice and the full citation on the first page. To copy otherwise, to republish, to post on servers or to redistribute to lists, requires prior specific permission and/or a fee.
UrbaNE'12, December 10, 2012, Nice, France.
Copyright 2012 ACM 978-1-4503-1781-8/12/12 ...$15.00.

networks, denoted *capillary networks*, which could provide a flexible link between the access network and the mobile devices. There are however several issues to tackle before turning the available interfaces from a bunch of incoherent technologies into a real capillary network able to be an answer to the smart city challenges.

2. SMART CITIES CHALLENGES

A prominent issue in the networking paradigm evolution is that it leaves the technical-only sphere and enters a combined technical and social one. Because there are no cities without citizens, users are a central concern in smart cities challenges, be it the metering their usage of cities' infrastructures, the gathering of crowdsourced digitalization of the city, or the delivery of user-centric services

2.1 Smart infrastructure

Unlike the communication infrastructure that went through a continuous development in the last decades, the distribution networks in our cities, either we are talking about water, gas, or electricity, are still based on 19th century infrastructure. With the introduction of new methods for producing renewable but unpredictable energy and with the increased attention towards environmental problems, modernizing distribution networks became one of the major concerns in the urban world. An essential component of these enhanced systems is their integration with information and communications technology, the result being a smart distribution infrastructure, with improved efficiency and reliability. This evolution is mainly based on the increased deployment of automatic equipment and the use of machine-to-machine and sensor-to-actuator communications that would allow taking into account the behavior and necessities of both consumers and suppliers.

Another fundamental urban infrastructure is the transportation system. The progress achieved by the transportation industry over the last century has been an essential factor in the development of today's urban society, while also triggering the birth and growth of other economic branches. However, the current transportation system has serious difficulties coping with the continuous growth in the number of vehicles, especially in an urban environment. As a major increase in the capacity of a city road infrastructure, already in place for tens or even hundreds of years, would imply dissuasive costs, the more realistic approach is to optimize the use of the existing transportation system. As in the case of distribution networks, the intelligence of the system will be obtained by the integration of information and communication capabilities. However, for smart transportation the challenges are somehow different, because the intelligence is no longer limited to the infrastructure, but propagates to vehicles themselves. Moreover, the degree of automation is reduced in transportation systems, as most actions resulting in reduced road congestion, higher reliability or improved safety must come from the human driver (at least in the foreseeable future).

Finally, smart spaces are becoming an essential component of our cities. The classical architectural tools used to design and shape the urban environment are more and more challenged by the idea of automatically modifying private and public spaces in order to adapt to the requirements and preferences of their users. Among the objectives of this new urban planning current, we can find the transformation of the home in a proactive health care center, fast reconfigurable and customizable workplaces, or the addition of digital content in the public spaces in order to reshape the urban scene [8]. Bringing these changing places in our daily lives is conditioned by a major shift in the construction industry, but it also involves important advancements in digital infrastructure, sensing, and communications

2.2 Urban sensing

Urban sensing can be seen as the same evolution of the environment digitalization as social networking has been for information flows. Indeed, besides dedicated and deployed sensors and actuators, still required for specific sensing operations such as the real-time monitoring of pollution levels, there is a wide range of relevant urban data that can be collected without the need for new communication infrastructures, leveraging instead on the pervasiveness of smart mobile terminals. With more than 80% of the population owning a mobile phone, the mobile market has a deeper penetration than electricity or safe drinking water [21]. Originally designed for voice transmitted over cellular networks, mobile phones are today complete computing, communication and sensing devices, offering in a handheld device multiple sensors and communication technologies.

Mobile devices such as smartphones or tablets are indeed able to gather a wealth of informations through embedded cameras, GPS receivers, accelerometers, and cellular, WiFi and bluetooth radio interfaces. When collected by a single device, such data may have small value per-se, however its fusion over large scales could prove critical for urban sensing to become an economically viable mainstream paradigm.

This is even more true when less traditional mobile terminals are taken into account: privately-owned cars [9, 10], public transport means [11], commercial fleets [12], and even city bikes [13] are starting to feature communication capabilities and the Floating Car Data (FCD) they generate can bring a dramatic contribution to the cause of urban sensing. Indeed, other than enlarging the sensing scope even further, e.g., through Electronic Control Units (ECUs) [14], these mobile terminals are not burdened by strong energy constraints and can thus significantly increase the granularity of data collection.

This data can be used by authorities to improve public services, or by citizens who can integrate it in their choices. However, in order to kindle this hidden information, important problems related to data gathering, aggregation, communication, data mining, or even energy efficiency need to be solved.

2.3 User-centric services

What is the most disobeyed traffic sign in your city? How does the level of pollution on your street compare with the one in other neighborhoods? How long is the queue at that exhibition you were planning to attend today? Combining location awareness and data recovered from multiple sources like social networks or sensing devices can provide answers to all these questions, making visible previously unknown characteristics of the urban environment.

Beyond letting their own devices or vehicles autonomously harvest data from the environment through embedded or onboard sensors, mobile users can actively take part in the participatory sensing process because they can, in return, benefit from citizen-centric services which aim at improving their experience of the urban life. Crowdsourcing applications have the potential to turn citizens into both sources of information and interactive actors of the city. It is not a surprise that emerging services built on live mobile user feedback are rapidly meeting a large success [15, 16, 17].

In particular, improving everyone's mobility is probably one of the main services that a smart city shall offer to its inhabitants and visitors. This implies providing, through network broadcast data or urban smart-furniture, an accurate and user-tailored information on where people should head in order to find what they are looking for (from a specific kind of shop to a free parking slot), on their current travel time estimates, on the availability of better alternate means of transport to destination. Depending on the context, such information may need to be provided under hard real-time constraints, e.g., in presence of road accidents, unauthorized public manifestations, or delayed public transport schedules.

In some cases, information can also be provided to mobile users so as to bias or even enforce their mobility: drivers can be alerted of the arrival of an emergency vehicle so that they leave the leftmost lane available, or participants leaving vast public events can be directed out of the event venue through diverse routes displayed on their smartphones so as to dynamically balance the pedestrian flows and reduce their waiting times.

3. CAPILLARY NETWORK PARADIGM

All the aforementioned challenges rely on efficient data communications, be it within a fixed infrastructure or with mobile devices and users. Network users' mobility is today widely managed through cellular networks. These feature a number of advantages, including pervasive geographical coverage, seamless connectivity, a good level of security and possibly guaranteed bandwidth and latency. However, the management of cellular infrastructures is expensive, their update more even so, and their capacity is about to be exceeded with the explosion of digital services. Moreover, the digital cities need a thin and dense digitalization of their citizens and infrastructures' activities which makes classical sensor solutions fail as discussed below. There is hence a need for a new networking paradigm capable of providing enough capacity and quality of service.

From the user point of view, there is only one network to access to data and applications, but from the point of view of operators, engineers, there are several access networks: wireless sensor networks to measure the physical world, the cellular networks (including 3G/4G) to handle mobility, mesh networks to support new applications and services. We propose to aggregate all these networks in the concept of *capillary network*. A capillary network is, for the user or end device, a link to Internet, whatever the link is. For engineers and researchers, a capillary network represents all the different possible paths we have from the user terminal to the access network. Providing the support for a digital city and for a digital society requires to focus on Capillary Networking issues. These issues include classical challenges related to sensor, mesh, or user-centric networks (such as cellular or vehicular networks), but also present important components generated by the urban environment.

3.1 Limits of networks for smart cities

The customer demands and expectations are constantly growing and the low flexibility of the highly centralized cellular paradigm starts to show its age. The emergence of 4G/LTE, the reduction of cell size and the partial offloading of data traffic via femtocells and dual-mode devices do not seem sufficient to accommodate the load induced by the spreading of recent capacity-hungry applications. According to Cisco, global mobile data traffic will increase 18-fold by 2016, whereas the network connections speeds will only increase 9-fold by the same year [7]. We are therefore in a strong need for new network paradigms to complement the traditional cellular infrastructure and increase the overall communication capacity in metropolitan areas.

The cellular infrastructure may prove inadequate also from the delay viewpoint. Indeed, forcing all communications to pass through the core network may prevent some interesting applications with hard real-time constraints, that could instead be realized if the cellular network was coupled with slimmer distributed network paradigms.

At the beginning of the 21st century, the European Community has launched several working groups on the digital societies. The initial goal was to monitor the consumption and dissipation of the energy provided to the end-user. Rapidly, operator-dependent networks appeared: one dedicated to gas monitoring, one focused on the electricity consumption, one dealing with garbage collection, and so on. This has already lead to the apparition of new players on the market, urban telecommunication operators, e.g. M2O, a joint company between Orange and Veolia.

However, the need for dense and numerous measurements of the digital city disqualifies the classical wireless sensor network paradigm "1 application, 1 network". This is no longer acceptable with respect to economical issues but also from the point of view of the society which follows carefully the deployment of wireless technologies (social acceptability, non-electromagnetic pollution, non-intrusive technologies). Urban sensor networks need the aggregation of these manifold wireless sensor networks into a few platforms which support several applications, several traffic properties, etc.

Whether we are talking about wireless sensors enabling smart spaces, communicating vehicles or information exchanged between pedestrians, the networks formed this way can sometimes present an extremely high node degree, up to several hundred neighbors. This can be particularly challenging for the MAC layer protocol, especially if the network is not centralized. In a distributed scenario, channel access schemes classically used in cellular networks, such as TDMA or OFDMA are difficult to implement, while CSMA/CA-based techniques like those in the IEEE 802.11 and IEEE 802.15.4 families present serious scaling issues.

Moreover, each sensing application has still its own quality of service requirements, particularly in terms of capacity, delay and reliability. For example, smart-metering applications need one measure per device and day with 90% reliability while a free parking slot should to be notified in 1 second in a city center at rush hours, at in few seconds at night in residential areas.

3.2 A wealth of capillary network interfaces

Beyond cellular networks, multi hop wireless mobile networks are now mature technologies and provide a wealth of connectivity surrounding mobile devices. These manifold networking interfaces define a new class of networks, denoted *capillary networks*, which could provide a flexible link between the access network and the devices.

Urban capillary networks represent a possible answer to the capacity and latency problems that the cellular network is today facing and that will grow worse in the next few years. More precisely, mobile terminals can take a significantly more active part in the communication system and become a key component of future urban capillary networks.

However, despite the major role mobile terminals are expected to play in this evolution, the way we use mobile phones today preserves an archaic touch: the user must be aware of the different technologies and their properties in order to manually switch between them to obtain the desired cost and quality of service for a certain application. This can be especially frustrating in an urban scenario, where several communication choices are usually present in parallel (cellular, Wi-Fi, Bluetooth, RFID, etc.), and the number of possible choices is expected to grow with the deployment of femtocells, cellular relays, ultra-wide band communication, or cognitive radios. Moreover, the user is generally not aware of the state of the radio channel in the different parts of the spectrum he can use at a certain moment, so his choice might be far from optimal. Turning away from this approach towards a user transparent communication necessitates new software solutions, but also important evolutions in collaborative sensing, energy efficient communications, or end-to-end transmission control.

A machine-to-machine (M2M) paradigm seams a promising approach in that objective. It allows the plethora of smartphones, tablets and units onboard vehicles to exchange data freely, without the need to constantly resort to the cellular infrastructure. If a M2M communication paradigm were adopted on a large scale, the mobile capillary network could easily relieve the cellular infrastructure from a consistent part of its data traffic load, both in the uplink and downlink directions. This would, e.g., be the case for FCD, which could be locally aggregated by vehicles before being uploaded to the fusion datacenter through the cellular network. On the downlink, studies have already proved that the dissemination of information to vast amounts of customers could affordably rely on M2M communication, reducing the cost of the cellular download by 90% [18, 19, 20].

Moreover, the availability of a mobile capillary network could easily reduce the communication delay over short-to-medium distances, reducing it to a few milliseconds, thus enabling applications that are not within in reach of the traditional cellular infrastructure.

However, the exact potential of large-scale urban mobile capillary networks is still to be exactly quantified. In particular, studies on the mobility of inhabitants of metropolitan areas are needed, so as to identify how the capacity of the M2M-based network evolves over time and space, as well as which are the structural strengths and weaknesses of such a time-varying network.

4. CAPILLARY NETWORKING ISSUES

Defining the notion of capillary network is the first step toward providing an efficient networking paradigm in urban environment which leverages the wealth of connectivity available to multi-interface devices. There are however several issues to tackle in order to enable capillary networks as an answer to the smart city challenges.

4.1 Characterizing urban networks

A typical urban capillary network will involve a set of different communication technologies like 4G/LTE, IEEE 802.11, WSN, inter vehicular communications and many others. Each technology relies on a set of mechanisms that were designed to provide a dedicated set of functionalities. Typical mechanisms include resource allocation, scheduling, error detection and correction, routing etc.

Dimensioning the operating parameters of such network mechanisms in order to provide the desired services while ensuring the network efficiency is a classical and yet a difficult issue. There are many directions to address this problem. For instance, one can refer to the network dimensioning and traffic-engineering approaches. Cross layer optimization and Self-Organizing nNetworks paradigm in 4G/LTE are also other perspectives to tackle this issue. However, given the complexity of the problem, most of the efforts concentrate on the mono-technological and/or the mono-service cases.

In the urban scenario, the heterogeneity of the technologies and the particularity of the urban services bring up new network-dimensioning challenges. The optimization has to be extended to the inter-technological perspective and to the mutli-services standpoint. The different technologies that compose the capillary network have to interoperate in a seamless and optimal way so that they can provide user-centric services with the desired quality of experience. Consider for instance, dimensioning the scheduling mechanism of a mesh network, which has to carry the traffic generated by different WSN in the city. Predicting the time and spatial distribution of the traffic generated by the different WSNs are clearly among the key elements that shall be considered. On the other side, a promising approach from a downlink standpoint is to estimate the judicious setting of an WSN aggregation mechanism accordingly with the time varying capacity of the mesh backbone level.

It is quite clear that these questions cannot be addressed without characterizing the features of an urban capillary network. This covers the geographical proprieties of the networks (distribution, density, nodes degree, mobility etc.) as well as the data traffic characteristics of urban services. Understanding these proprieties and their correlation is still an uncovered area. A main challenge being the production of quantitative traces from real or realistic urban mobility, networks and services. As for an example, in urban mobility scenarios, how long "devices" are in radio range of each other gives temporal constraints on the communications protocols that should be understood. In this duration, devices have to self-organize or to hang on the exiting organization and to exchange information.

A second step is to derive analytical or simulation models that will be used for network dimensioning and optimization. Many models already exist in the literature in related scientific fields and they could be considered or adapted to this purpose. This covers different models ranging from radio propagation, vehicular or pedestrian mobility, traffic pattern etc. The difficulty being on how to mix these models and how to choose the right time magnitude and spatial scale in order to preserve the accuracy of the capillary network features while maintaining the model complexity tractable.

The derived models could serve to optimize the different mechanisms involved in the urban capillary network. It is quite clear that the inference between different networks and services is quite complex to understand and to model. A simple approach would be to decouple the models. Choosing the right decoupling technique depends on the targeted temporal/spatial level of the input and output parameters. Again, the latter shall capture for each decoupled model a selected set of significant features of the capillary network.

Finally, the purpose of the constructed models is to obtain the optimal dimensioning of the network mechanisms. Several optimization techniques, from exact to heuristics ones, shall be considered to compute the best operating parameters. One of the main challenges here is to maintain the computational complexity tractable by exploiting the specific structure of the problems induced by the city.

4.2 Highly scalable protocols

Even though there is no specific model of urban networks, some experiments show that the networks formed this way can sometimes be particularly challenging for the MAC layer protocols and QoS support, especially if the network is not centralized or synchronized: very high node degree, unstable and asymmetric links, ...

MAC layer protocols are whether very difficult to implement in distributed and self-organized environment or present serious scaling issues. Studies focusing on distributed TDMA (e.g. [22]) showed that MAC protocols from this class can be successfully designed to accommodate channel access for a high number of contending nodes. However, scalability is always obtained following a learning phase with relatively high convergence time. This means that in a dynamic network scenario like the one encountered in most urban capillary networks, the MAC protocol spends most of the time in the learning phase, where it achieves a reduced performance. The same problem appears when trying to distribute other usually centralized schemes, such as OFDMA or CDMA. On the other hand, CSMA/CA protocols are distributed by their nature. However, the current leading solutions in this area are based on the IEEE 802.11 Distributed Coordination Function (DCF), a channel access method designed and optimized for Wireless LANs with a central access point and a maximum of 10-20 contending stations. The DCF is well-known for its scalability issues, especially in multi-hop dynamic networks [23], and adding energy constraints usually existing in wireless sensor networks does not improve its performance [24]. While multiple MAC layer congestion control solutions have been proposed in the context of mobile ad-hoc networks, the approach is usually based on the idea of reducing the number of neighbors, either through transmission power control or data rate adjustment. However, this is just a workaround and the search for a truly scalable MAC layer protocol for high density wireless networks is still open.

For multi-service platforms to be deployed in practice, all telecommunication operators requirements should be present, in particular in wireless sensor and actuators networks, within the key notion of Service Level Agreement (SLA) for traffic differentiation, quality of service support (delay, reliability, etc.). Moreover, because the world becomes more and more connected to Internet, IP should be supported in wireless sensor networks. If IETF proposes the use of RPL (Routing Protocol for low power and lossy networks), it is clear that the support of several DoDAG is required, and a complete traffic management is needed. Moreover, RPL assumes a static topology but, the classical sensor networks give way to urban sensing , where the user's smartphone give the physical measures to the operators. Therefore, the data collection becomes distributed, sometimes localized, the network is now dynamic. In such a scenario, incoherences stemming from data collected using different calibration process claim a lot of interests. Moreover, data aggregation and data gathering is, in capillary networks, at the heart of the issues related to the limited capacity of the networks. In particular, combining local aggregation and measurement redundancy for improving on data reliability is a promising field.

4.3 Optimizing cellular network usage

As discussed in Section 3.1, the capacity of cellular networks, even those that are now being planned, does not seem able to cope with the increasing demands of data users. Moreover, new applications with high bandwidth requirements are also foreseen, for example in the intelligent transportation area, and an exponential growth in signaling traffic is expected in order to enable this data growth. Cumulated with the lack of available new spectrum, this leads to an important challenge for mobile operators, who are looking at both licensed and unlicensed technologies for solutions.

Several approaches can be taken to tackle this problem, the most obvious being to exploit the capillarity of network interfaces for preventing data to go through the cellular network. In this perspective, taking advantage of the fact that cellular operators usually possess an important ADSL or cable infrastructure for wired services, the development of femtocell solutions has become very popular. However, while femtocells can be an excellent solution in zones with poor coverage, their extensive use in areas with a high density of mobile users leads to serious interference problems that are yet to be solved. Taking advantage of capillarity for offloading cellular data is to use IEEE 802.11 Wi-Fi (or other multi-hop technologies) access points or direct device-to-device communications.

The ubiquity of Wi-Fi access in urban areas makes this solution particularly interesting, and many studies have focused on its potential (e.g. [25]), concluding that more than 65% of the data can be offloaded from the cellular infrastructure in high density areas. However, these studies fail to take into account the usually low quality of Wi-Fi connections in public areas, and they consider that a certain data rate can be sustained by the Wi-Fi network regardless of the number of contending nodes. In reality, most public Wi-Fi networks are optimized for connectivity, but not for capacity, and more research in this area is needed to correctly assess the potential of this technology. Direct opportunistic communication between mobile users can also be used to offload an important amount of data [26]. This solution raises a number of major problems related to the role of social information and multi-hop communication in the achievable offload capacity. Moreover, in this case the business model is not yet clear, as operators would indeed offload traffic, but also lose revenue as direct ad-hoc communication would be difficult to charge and privacy issues may arise. However, combining hotspot connectivity and multi-hop communications is an appealing answer to broadcasting geo-localized informations efficiently.

A complementary approach, more operator oriented, for minimizing the transmission power of cellular networks as well as increasing the network capacity, consists in a dramatic densification of micro-cells coverage [27]. On the other hand, increasing the number of micro-cells multiplies the energy consumed by the cells whatever their state, idle, transmitting or receiving, which is a major and growing part of the access network energy consumption [28]. For a sustainable deployment of such micro-cell infrastructures and for a significative decrease of the overall energy consumption, an operator needs to be able to switch off cells when they are not absolutely needed [29]. The densification of the cells induces the need for an autonomic control of the on/off state of cells, which can be done by mechanisms inspired by the abundant works on WSNs [30, 31] and adapted to the energy models of micro-cells, and to the requirements of a cellular network, in particular the need for providing an adequate quality of service to dynamic and mobile clients.

5. CONCLUSION

The authors of this paper are the members of the new Inria/INSA Lyon team Urbanet. In this paper, we have presented our vision of the networking challenges induced by the rise of Smart Cities. Our standpoint is that enabling Smart Cities yields the need for an adequate networking paradigm. Our team focuses on *capillary networks* which unify the wealth of wireless connectivity available in urban environment. We have presented the main research issues that we identify as the key problems that should be solved by the wireless networking community.

6. REFERENCES

[1] UNO Economic and Social Affairs. World Urbanization Prospects The 2009 Revision. Technical report, United Nations, 2010.

[2] Expo 2010 Shanghai, China. `http://en.expo2010.cn`.

[3] European Smart Cities project, `http://www.smart-cities.eu`.

[4] ICT Lab Digital Cities of the Future, European Institute of Innovation & Technology `http://www.eitictlabs.eu/action-lines/digital-cities-of-the-future`

[5] City Science, MIT Media Lab, `http://cities.media.mit.edu`.

[6] European Union, *"Commission launches innovation partnership for Smart Cities and Communities"*, press release, July 2012, available online at `http://europa.eu/rapid/press-release_IP-12-760_en.htm`.

[7] Cisco, *"Cisco Visual Networking Index: Global Mobile Data Traffic Forecast Update, 2011–2016"*, White Paper, 2012.

[8] MIT Media Lab, *Changing Places and House, Research Topics*, available online at `http://web.media.mit.edu/~kll/`

[9] TomTom, *"How TomTom's HD TrafficTM and IQ RoutesTM data provides the very best routing"*, White Paper, 2010.

[10] Meihui Software, available online at `http://www.meihuichina.com`.

[11] H. Zhu, M. Li, Y. Zhu, L.M. Ni, "Hero: Online real-time vehicle tracking", *IEEE Transactions on Parallel and Distributed Systems*, vol.20, no.5, pp.740–752, May 2009.

[12] Cab Spotting, `http://cabspotting.org/api`.

[13] The Copenahagen Wheel, `http://senseable.mit.edu/copenhagenwheel`.

[14] R.N. Charette, *"This car runs on code"*, IEEE Spectrum, February 2009.

[15] Google Maps for mobile, `http://www.google.co.uk/mobile/maps`.

[16] Coyote Systems, `http://www.coyotesystems.co.uk`.

[17] Waze – outsmarting traffic together, `http://www.waze.com`.

[18] J. Whitbeck, Y. Lopez, J. Leguay, V. Conan, M. Dias de Amorim, *"Relieving the wireless infrastructure: when opportunistic networks meet guaranteed delays"*, IEEE WoWMoM, Lucca, Italy, June 2011.

[19] B. Han, P. Hui, V.S.A. Kumar, M.V. Marathe, G. Pei, A. Srinivasan, *"Cellular traffic offloading through opportunistic communications: a case study"*, ACM CHANTS, Chicago, IL, USA, September 2010.

[20] F. Malandrino, C. Casetti, C.-F. Chiasserini, M. Fiore, *"Offloading Cellular Networks through ITS Content Download"*, IEEE SECON, Seoul, Korea, June 2012.

[21] C. Sharma, *Global Mobile Market Update*, available online at `http://www.chetansharma.com/GlobalMobileMarketUpdate2012.htm`

[22] F. Yu, S. Biswas, "Self-Configuring TDMA Protocols for Enhancing Vehicle Safety with DSRC based Vehicle-to-Vehicle Communications", *IEEE Journal on Selected Areas in Communications*, vol. 25, no. 8, pp. 1526-1537, October 2007.

[23] S. Xu, T. Saadawi, "Does the IEEE 802.11 MAC Protocol Work Well in Multihop Wireless Ad Hoc Networks?", *IEEE Communications Magazine*, vol. 39, no. 6, pp. 130-137, June 200.

[24] T. McHenry, J. Heidemann, *MAC Stability in Sensor Networks at High Network Densities*, Techincal Report ISI-TR-2007-628, University of Southern California, January 2007.

[25] K. Lee, J. Lee, Y. Yi, I. Rhee, S. Chong, *Mobile Data Offloading: How Much Can WiFi Deliver?*, IEEE/ACM Co-NEXT 2010, pp. 1-12, December 2010, Philadelphia.

[26] B. Han, P. Hui, V. Kumar, M. Marathe, G. Pei, A. Srinivasan, *Cellular Traffic Offloading through Opportunistic Communications: A Case Study*, ACM CHANTS 2010, pp. 31-38, September 2010, Chicago.

[27] A. Fehske, F. Richter, and G. Fettweis, *Energy efficiency improvements through micro sites in cellular mobile radio networks*, (Dresden, Germany), IEEE GLOBECOM Workshops, December 2009.

[28] ITU-T and climate change, *ICTs and Climate Change, ITU-T Technology Watch Report*, available online at `http://www.itu.int/ITU-T/climatechange/`

[29] M. Marsan, L. Chiaraviglio, D. Ciullo, and M. Meo, *Optimal energy savings in cellular access networks*, (Torino, Italy), IEEE Communications Workshops, June 2009.

[30] C. F. Huang, Y. C. Tseng, and H. L. Wu, "Distributed protocols for ensuring both coverage and connectivity of a wireless sensor network", *ACM Transactions on Sensor Networks*, vol. 3, March 2007.

[31] A. Gallais, J. Carle, D. Simplot-Ryl, and I. Stojmenovic, "Localized sensor area coverage with low communication overhead", *IEEE Transactions Mobile Computing*, vol. 7, May 2008.