Wireless Pers Commun (2010) 53:365–393
DOI 10.1007/s11277-010-9952-4

# Wireless Innovations as Enablers for Complex & Dynamic Artificial Systems

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**Abstract** Scientific and technological innovations of the last few decades in the field of wireless telecommunications and networking have enabled a wide area of applications and services in healthcare, transportation, environmental protection, infotainment, industrial automation, homeland security, smart urban environments and other disparate fields. At the same time the complexity and criticality of these systems creates many technical challenges in their design, development and operation. This paper reviews a number of important application fields of wireless communications and networking and discusses recent results, key challenges and unsolved issues in each one of them. It goes on to present some theoretical and practical issues and research directions in the field of wireless communications and networking that are common to most if not all application areas. These include theoretical link and network capacity limits, cognitive radio and cognitive networking, programming and in-field reprogramming of wireless devices, and complex system design inspired by biology and physics.

**Keywords** Wireless communications · Wireless networks · MANET · WSN · VSN · VANET · Pervasive health · Nanotechnology · Industrial automation · ITS · Telematics · Mobile sensor networks · Intelligent city · Environmental risk management · MANET capacity · Cognitive radio · Cognitive network · Sensor network programming · Middleware · Biology inspired · Physics inspired

## 1 Introduction

In the last two decades, the world has witnessed an exponentially increasing technological development and commercial success of wireless technologies. This explosive

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growth of wireless telecommunications was lead by cellular telephony, followed by data communications initially in WLANs and now increasingly in cellular networks. One of the major ongoing trends that are transforming the telecommunications landscape worldwide is that "the Internet is going wireless".

According to data presented in [1], the global number of servers/PCs with a wired connection to the Internet was estimated at 500 million in 2005, 600 million in 2008 and is expected to reach 1 billion by 2015. At the same time, more than 3 billion cellular phones were in operation worldwide in 2008 out of which more than 500 million were subscribed to IP services with the number increasing rapidly. Finally, the number of laptops, PDAs, wireless sensors and other small devices with wireless communication capabilities is exhibiting the most impressive growth: in 2005 an estimated 100 million laptops and PDAs were in operation while in 2015 the total number of laptops, PDAs, cell phones, wireless sensors and other devices with wireless network connectivity is expected to exceed 10 billion.

Wireless telecommunication capable devices are getting smaller, cheaper and more powerful. With the advent of Wireless Sensors, RFID tags and other smart networked devices, many researchers believe that we are moving fast towards the "Internet of things" when billions or even trillions of interconnected devices are going to constitute a big portion of the edge of the future Internet. According to a 2004 report by IDC, 17 billion networkable devices (including computers, handhelds, entertainment devices, industrial/automotive nodes, and other appliances/toys) are expected to be installed worldwide by 2012. Sun Microsystems estimates that including sensors and RFIDs the world could have *a trillion* communicating devices in a decade [2].

Needless to say that the complexity of such an extremely large scale, diverse and dynamically changing network is creating major design and technical challenges. Embedded Internet Systems (EIS) in every appliance, wireless sensors monitoring environmental parameters and RFIDs in most commercial products will be generating a huge amount of data traffic. This extremely large scale, ubiquitous network faces inevitable protocol scalability issues, while the small size of many of its nodes creates resource constraints under which critical embedded wireless requirements must be satisfied. Specific requirements of the future Internet are high reliability and adaptability, long lifetime on limited energy resources, addressing and service discovery, manageability of such a large system including in field software upgrading and reprogramming. The Internet is undergoing a paradigm shift from a model where each network node was directly supervised by a human user or administrator to a model where most nodes will be unattended, inaccessible networked devices connected to the physical world, sometimes engaged in critical functions [3,4]. These nodes have to be simple, robust, reliable, resilient, provable and self-sufficient. The individual nodes and the network as a whole must be able to organize, operate, adapt, heal and reconfigure by itself without any human intervention.

At the same time, the pervasiveness, versatility, increasingly lower cost and higher capacities of wireless nodes and networks make possible novel applications in a variety of exiting fields such as healthcare, transportation, environmental protection, infotainment, industrial automation, homeland security and smart urban environments. The most groundbreaking and futuristic of these application domains and the associated wireless technologies is nanotechnology. The recent and ongoing technological breakthroughs in the field of nanotechnology have created the need for wireless communications at the nano-scale. In order to enable nanodevices to communicate with each other, novel wireless communication techniques must be employed that are not based in traditional electromagnetic or sound waves transmission and reception. These techniques are bio-inspired in an effort to mimic the ways living cells and micro-organisms communicate with each other.

This paper attempts to present the most important application fields that are enabled by wireless innovation and review some characteristic examples of research projects and recent results in each field. At the same time, emphasis is given in identifying open issues and characterizing the major sources of complexity in each application field as well as fundamental issues in the forefront of wireless communication and networks research.

The rest of this paper is organized as follows: in Sect. 2 an overview of several application domains of wireless communications and network technologies is provided. These domains include, pervasive health, nanotechnology, industrial automation, Intelligent Transport Systems, mobile sensing, environmental risk management and the Intelligent digital city. Section 3 discusses fundamental theoretical and technical issues that are in the core of recent and ongoing research in the field, including link and network capacity limits, cognitive radio and networks, sensor programming and in-field reprogramming, and the application of biology and physics inspired designs to emerging complex problems and systems. Finally, Sect. 4 concludes the paper.

## 2 Wireless Innovations in Characteristic Application Domains

In this Section we review the most important application domains in the forefront of scientific and technological research that are enabled by wireless innovations and are still faced with unsolved issues mostly arising from system and application complexity. For each one of the following domains, a number of important research initiatives are described and the major complexity issues are discussed.

### 2.1 Pervasive Healthcare

In his 2006 book with the provocative title "The End of Medicine: How Silicon Valley (and Naked Mice) Will Reboot Your Doctor" [5], author Andy Kessler envisions the day when diagnostic examinations will be carried out by non-expensive, tiny, implantable sensors that will perform continuous monitoring and enable early detection of health risks such as growing cancer tumors and cardiovascular diseases. As a matter of fact, intensive research efforts are under way to achieve the end of *traditional* medicine.

In the *traditional primary healthcare delivery model* a patient detects a symptom and visits a medical facility where a medical practitioner takes medical history, vital signs and/or the results of other specialized medical tests and uses them to diagnose the condition and then prescribe treatment appropriately. Apart from being a tiring manual process for the medical professional, this model is rather reactive, slow, costly and inefficient. In recent years, a large number of research and commercial projects have proposed a wide range of medical applications where the use of wireless communication plays a pivotal role. A number of innovative new devices and applications have emerged that rest on wireless technology in order to: offer to the doctor quick and easy access to medical records and lab results whether from the surgery room, the hospital, the patient's home or site of accident; permit the remote monitoring of vital signs in clinical, emergency or outpatient situations; reduce the cost of outpatient monitoring and in some cases, streamline the data logging process in medical facilities. The result of all these innovations is a new healthcare model, the *pervasive healthcare* model, which is proactive, automated, real-time, cost-effective and very efficient. The goal of pervasive healthcare is to provide continuous patient monitoring enabling automated diagnosis and treatment while utilizing medical facilities only if the patient's condition is very serious

[6]. In [7] pervasive healthcare is defined as healthcare to anyone, anytime, and anywhere by removing location, time and other restraints while increasing both the coverage and the quality. Pervasive (or ubiquitous [8–10]) healthcare applications come in many forms including pervasive health monitoring, intelligent emergency management systems, pervasive healthcare data access, and ubiquitous mobile telemedicine. Pervasive healthcare solutions can also target healthy individuals as in athletes monitoring for performance optimization, personal fitness monitoring and healthy nutrition and life habits reinforcement applications.

Important research projects that have advanced the state of the art in the area of pervasive healthcare include (cf., [11] and references therein): Proactive Health (Intel), Code Blue (Harvard University), Scalable Medical Alert and Response Technology—SMART (MIT, Harvard, Brigham and Women's Hospital), Ayushman (Arizona State University), Aware (University of Aarhus, Denmark), Advanced care and alert portable telemedical MONitor—AMON (EU IST FP5 project), Ubiquitous Monitoring Environment for Wearable and Implantable Sensors—UbiMon (DTI funded—Lancaster University and Imperial College London), Sports Body Sensor Networks—Sports-BSN (Imperial College, UK), MobiHealth and HealthService24 (EU IST projects), Ericsson Mobile Health—EMH (Ericsson), HeartCycle (EU IST FP7 project) and many others.

One of the key challenges of pervasive healthcare solutions is to gain user acceptance by being minimally intrusive and obstructive to the patients' every day life. This can be achieved by the miniaturization of medical sensors and actuators that can be placed inside the body (implanted or ingested) or on the body (in the form of a skin patch, an accessory or a shirt) and use wireless transmission to send important sensed information to its appropriate destination (usually an on-body gateway and from there to a home PC, a doctor's cell phone or a hospital's control center). In fact many research projects and commercial products have achieved to reduce the size of various vital sign sensors to extremely small levels (Fig. 1). A whole range of sensors are now available that can measure vital signs such as temperature, blood pressure, heartbeat, $SpO_2$ (blood oxygen saturation), glucose level, breathing rate, can detect the body's position and acceleration, the number of steps taken while walking, can perform continuous electrocardiogram (ECG), electroencephalogram (EEG) and electromyograms (EMG) and can provide diagnostic images, video and sound (for example a miniscule camera inside an ingestible micro-capsule is used to obtain diagnostic images of the gastrointestinal system). Sensors or RFID tags can also be placed on the patient's bed, a medicine container or even into medication. For example, Proteus Biomedical is developing a technology to incorporate tiny digestible sensors into medications such as a pill treating high blood pressure, schizophrenia or heart failure [12]. Once a patient swallows the chip-containing pill, stomach acids activate the sensor which collects and wirelessly transmits information such as the type of drug and patient vital signs. The receiver can also infer the time the pill was taken thus testing the patient's drug compliance. Combined with medical sensors, special purpose actuators can be used to provide a feedback control mechanism. For example, an insulin pump is an actuator which pumps insulin to the body whenever the sensor-measured glucose level exceeds a set threshold. A robotic prosthetic might be used in the future in conjunction with a brain-machine interface to improve the kinetic abilities of a paralyzed person [13].

Medical sensors and actuators on a single patient form a wireless Body Area Network (BAN) [14]. As mentioned above, at least one on-body device in the BAN has greater computational capabilities and acts as the gateway of the BAN to other networks. This device is referred to with many names in the literature such as a Local Processing Unit [15], a Mobile Base Unit [17,18], a Personal Server [19,20], a Body Area Aggregator [14] and a Local Gateway [10]. Extra-BAN communication between the Local Gateway and external

**Fig. 1** Examples of medical sensors for pervasive health care applications (*source*: *Ayushman project, ASU* [10])

networks is commonly carried out over standard WLAN and WWAN protocols. Intra-BAN communication can be wired or wireless. For wireless intra-BAN communication, standard WPAN protocols (such as Zigbee, Bluetooth, WiBree, 802.15.4, etc.) are suitable in case the two communicating nodes are on the body. For implanted sensors designing a suitable wireless communication protocol is quite challenging for two reasons. First, electromagnetic waves attenuate rapidly through the tissues of the body. Second severe transmit power limitations to implanted transmitter are caused by both the safety constraint that the surrounding tissues' temperature should not be raised by more than 1°C and the difficulty to power up a tiny sensor implanted in the human body [13]. In [16], the authors applied IEEE 802.15.4b and 802.15.4a—chirp spread spectrum (CSS) for medical implant communication and found clear channel assessment of implant devices and adjacent-channel interference from free space signals as critical issues. They concluded that the CSMA mechanism and transmit mask of 802.15.4b cannot be adopted directly for implants since they behave differently due to the rapid attenuation of electromagnetic waves through the tissues of the body.

For all the above reasons, some RF communication standards and proprietary protocols (such as MICS—Medical Implant Communication Service [21]) have been developed specifically for wireless communication with implants. Other proposed solutions include the use of ultrasound waves [22], infrared or even optical communication [13] through the human skin. However, current state of the art still poses constraints to data rate demanding applications such as brain-machine interfaces [13]. Until higher data rate protocols are developed, researchers are trying to reduce the data rate requirements of such applications by employing novel application specific data compression techniques.

Other challenges in the field of wireless communications support for pervasive healthcare include resolving privacy, security and regulatory issues, ensure system robustness and QoS—especially in life critical applications—with back-up solutions in case of some hardware, software or network failure (e.g., the case when the patient moves outside of the coverage of all cellular WWAN networks), plan for system scalability when millions of people will be using pervasive healthcare services and design interoperable systems and products. Regarding this last issue, current medical device technologies are proprietary and scattered, and need harmonization. A number of standard specifications have been or are currently being developed or improved to address this problem [23] such as the Personal Healthcare Device (PHD) Class Specification by USB Implementers Forum (USB-IF), the ISO/IEEE 11073 Personal Health Device Specifications, the Medical Device Profile (MDP) in Bluetooth SIG, the ZigBee Health Care application profiles, as well as standards being developed in the IEEE 802.15 Task Group 6 which will include new PHY and MAC standards for WBANs [24].

### 2.2 Nano-Devices and Nano-Networks

As mentioned in the previous subsection, miniaturization of medical sensors is the key to many medical applications. At the micro-scale, Micro Electro-Mechanical System (MEMS) devices such as implantable sensors or pill-sized endoscopic cameras can still use RF wireless communications. At the nano-scale (devices ranging from 1 to 100 nm large) it is difficult to use electromagnetic waves for communication because the current complexities of the transceivers prevent them from being integrated into nano-devices and the output power may be too small to establish bidirectional communication. Miniaturization at the nano-scale level is the goal of *nanotechnology* which is defined as "the processing of, separation, consolidation, and deformation of materials by one atom or by one molecule" [25]. The most basic functional unit at the nano-scale level is called a *nano-machine* (or Nano Electro-Mechanical System, NEMS). Nano-machines are tiny artificially engineered components consisting of an arranged set of molecules which are able to perform very simple computation, sensing and/or actuation tasks [27]. Nanotechnology is a very exciting rapidly growing field with applications in a wide array of scientific and technological disciplines. The US federal government budgeted $464 million for nanotechnology research in 2001 which increased to $1.6 billion in 2010.

Nanotechnology applications include developing new materials or improving the manufacturing process of existing materials, reducing the size of electronic circuits and invent new structures and methods for information processing (e.g., quantum or biologically inspired computing), and developing new nano-devices with sensing, optical communications, data storage, medical, biological, military, environmental, energy generation, oil exploration and other applications. In some futuristic scenarios that extend the medical applications described in Sect. 2.1, nano-robots will roam in the human body to diagnose and fight diseases (e.g., by attacking infectious agents and cancer cells), repair damaged organs or even individual cells, deliver drugs in the appropriate quantity, place and time, relieve pain and contribute in the health conservation and anti-aging of the human body.

Some representative projects / initiatives in this area are: the NASA Institute for Advanced Concepts Phase II Grant, the NSF NanoManufacturing and Active Nanostructures and Nanosystems programs, the Arizona Institute for Nano-electronics (AINE) [28], the Bio Nanorobotics Laboratory at Northeastern University in Boston [29], and the EU funded project NANOMA—NanoActuators and NanoSensors for Medical Applications [30].

Biologically inspired nano-machines are envisioned to be able to self-organize, learn, self-replicate using external elements, move from one place to another and communicate in order to learn from others and perform collective tasks. Since traditional RF wireless communication is not applicable in this scale, novel bio-inspired ways of communication have been proposed. The envisioned means of communicating among nano-machines is called *molecular communication.* Molecular communication is an interdisciplinary field that spans nano-, bio- and communication technologies, and allows biological and artificially-created sensors to communicate with each other using molecules [26,27]. In molecular communication the sender encodes information in a *molecular message* which is a molecule that can be easily recognized by the receiver, is not prone to react with other molecules in the medium, and can be easily discarded or reused at the receiver after it has been decoded. The molecular message is emitted by the sender in a controlled manner so that it will reach the receiver with some non-zero probability. If this probability is small, more than one duplicate molecular-messages are sent to increase the probability of reception. Information molecules can be attached to or enclosed in carrier molecules which are more suitable for controlled propagation as shown in Fig. 2. For example, one proposed molecular communication design [31] uses vesicles

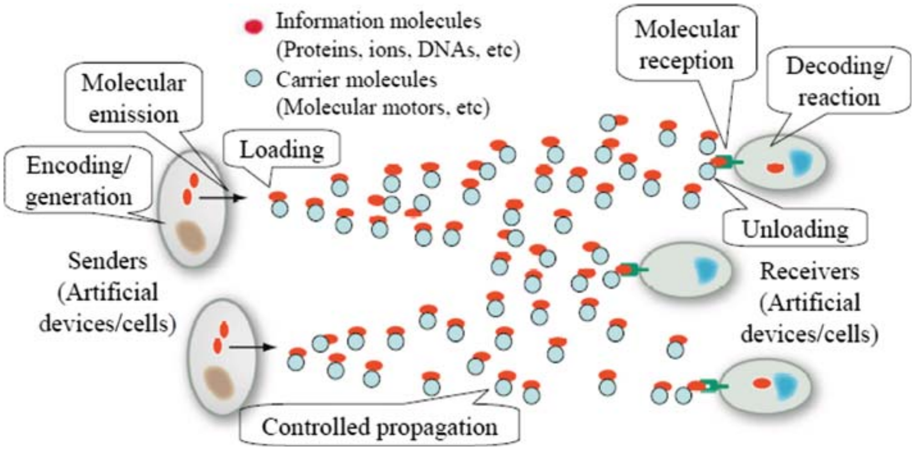

**Fig. 2** An example molecular communication system (*source*: [27])

to wrap the information molecules and conceal their characteristics so that the propagation system is designed to transport vesicles independently of the characteristics of information molecules contained in these vesicles.

As the field of communications in the nano-scale is still in its infancy, there is a long road ahead until such communication schemes can become practical and reliable. Every aspect of wireless communication in this scale, from information-theoretical channel capacity characterization to transceiver design and from Medium Access Control and reliable transmission schemes to addressing and routing need to be investigated, redesigned and applied anew for this very different form of communication. Furthermore, nanotechnology in general and nano-communications in particular are a cross-disciplinary field which require knowledge of physics, biology, chemistry and engineering to understand and make successful system designs in the nano-world. Additional challenges stem from the extremely small size of nano-devices such as the difficulty and high cost of fabricating and testing the designed devices as well as the current lack of simulators for nano-communications and nano-networks. Power, memory and computational efficiency constraints will pose severe limitations as well. Nano-machines are expected to perform complex tasks by exploiting their large number: each one exhibits a simple functionality but their combined force is more than the sum of the parts (as with the cells in a living organism). Providing power and closed loop control and guidance to nano-devices is yet another challenge. Finally, in applications were a very large number of nano-machines will need to cooperate, protocol scaling issues will arise as well. However, the existence of a very large number of nano-machines might solve reliability problems as it might be sufficient for an application that only a fraction of the involved machines receive a message and perform a certain function.

### 2.3 Automation and Control Using Embedded Sensors and Actuators

The availability of small-sized, non-expensive sensors and actuators that can communicate wirelessly, has inspired a variety of applications that can be collectively described as monitoring and control of the physical and man-made environment. In this subsection, we focus on applications of industrial control and building automation that are based on wireless networking of sensors and actuators. Industrial automatic control strongly depends on wired networks of sensors and actuators that have been studied and standardized for a long time and to that extent they can be considered a very mature technology. However, the use of wireless communications instead of wired links would offer the significant advantage of mobility (i.e., the ability to attach sensors and actuators to humans, moving devices or materials for the purpose of tracking, locating and collecting data about them) and fast and less expensive network expansion. The Wireless Industrial Networking Alliance (WINA) is a coalition of industrial end-user companies, technology suppliers, industry organizations, software developers, system integrators, and others interested in the advancement of wireless solutions for industry [32]. According to WINA, "wireless technology and wireless networking systems hold great promise to help industry use energy and materials more efficiently, lower systems and infrastructure costs, lower production costs, and increase productivity." At the same time, it is widely recognized that wireless communications in an industrial environment face many challenges. First, the propagation environment and electromagnetic interference in an industrial setting is very hostile. A typical process pant is like "canyons of metal". High vibrations, high humidity, extreme temperatures and high EMF/RF noise and interference from other wireless transmitters are common issues. In certain cases where explosive gases or other hazardous materials are present, all electronic appliances (including wireless transceivers) must satisfy standard safety specifications. The robustness and strict QoS requirements of the industrial control applications must be met by the wireless network under these harsh conditions. Network and data security is also of paramount importance in industrial applications. Finally, the complexity of large industrial installations is tremendous with thousands of machines, processes, networked devices, software applications, data streams to be transmitted and stored, variables to be monitored and decisions to be made. Therefore, wireless protocols in this environment must be scalable, robust, and efficient and allow for integration and co-existence with other wireless and wired protocols used in other sub-networks in the same plant.

Short and medium range wireless networking protocol standards designed for sensing and control applications include WirelessHART [33], Zigbee, 6lowpan [35] and ISA100.11a. Other generic wireless communication standards (such as WiFi, Bluetooth, WiMAX, and cellular) are also used in this field. ZigBee is a mesh networking standard (building on top of IEEE 802.15.4) intended for uses such as embedded sensing, medical data collection, consumer devices like television remote controls, and home automation. WirelessHART is an extension of the HART (Highway Addressable Remote Transducer) Protocol and is specifically designed for industrial applications like Process Monitoring and Control. 6lowpan is the IETF standards track specification for the IP-to-MAC-Layer mapping for IPv6 on IEEE 802.15.4. ISA100 [34] is a new family of wireless standards for process plant automation under development by the International Society of Automation (ISA). ISA100.11a was the first protocol in the ISA100 family to be ratified in September 2009. It is an industrial wireless automation standard for process plants focusing on security, co-existence with other wireless standards and interoperability with existing wired plant automation protocols.

Most wireless protocols and applications for industrial automation and control are developed by the industry. However, a lot of academic research is dedicated to problems of control under limited, noisy or delayed feedback information. Such problems arise when control is exercised over a communications network, and are even more relevant in the face of communication over wireless channels. Three indicative projects in this area are the DARPA funded "*Communicating Networked Control Systems*" Multidisciplinary University Research Program (MURI) at four US Universities, the EU funded HYCON Network of Excellence, and the Finnish—Swedish project WISA (Wireless Sensor and Actuator Networks for Measurement and Control). Work in HYCON has reached the conclusion that current layered network protocols are not suitable for control applications and have proposed a cross-layer, energy efficient protocol for wireless sensor networks used for control and automation [37].

### 2.4 Intelligent Transport Systems

Another important application of embedded networked electronic devices that benefits from the recent advances in wireless ad hoc networks is *Automotive Telematics* and *Intelligent Transport Systems* (ITS). In recent years, a great variety of Information and Communication Technologies (ICT) devices and applications have found their way into commercial vehicles. Vehicular ICT is now changing the way that people use their cars, making transportation systems safer and more efficient. Starting with a wide range of stand-alone devices, such as GPS assisted navigators, DVD players and hands free mobile phones, telematics is now maturing into an integrated hardware and software platform that will support a variety of diverse applications. This emerging architecture consists of a central computer with a powerful operating system, connected to various embedded microprocessors in the vehicle via a Car Area Network and communicating wirelessly with the passenger's personal electronic devices, other vehicles or the roadside infrastructure and the Internet.

Direct Vehicle-to-Vehicle (V2V) and Vehicle-to-Roadside (V2R) wireless communication allows vehicles and roadside devices to form ad hoc networks and exchange information without the need for a costly WWAN infrastructure and service. Not only this ad hoc topology minimizes cost but it can also drastically increase capacity as short range wireless links can offer much larger data rates. Another suggested network architecture employs the Infostation concept. Infostations are fixed wireless Access Points attached to an information server or the entire Internet. They are located along highways on street lamps, gas stations or other strategically selected locations and offer isolated pockets of high bit rate in their immediate vicinity. Passing-by or stopping-by vehicles have a smaller or larger window of opportunity to communicate with the Infostation and download a large amount of data such as location based information or a (portion of) an on-demand video. A lot of effort has been devoted in developing wireless protocols for short range V2V and V2R communication as well as MAC [36] and routing protocols for vehicular MANETs (also known as VANETs).

In 1999, the Federal Communications Commission (FCC) of the USA dedicated 75 MHz of wireless spectrum within the 5.9 GHz band (5.850–5.925 GHz) for a new Dedicated Short Range Communication service [38] to be used for V2V and V2R wireless communication. The first protocol for wireless communications in the DSRC band was ASTM E2213-03. The PHY and MAC layers defined in ASTM E2213-03 extend IEEE 802.11a for use into the high-speed vehicular environment. Currently, the IEEE 802.11p Task Group is working on a successor to the ASTM E2213-03 standard which is expected to be published in November 2010. IEEE 802.11p will combine with the IEEE 1609 family of standards to constitute a full-fledged protocol suite for Wireless Access in Vehicular Environments (WAVE) [39].

Potential applications of ITS include: information and warning functions (road information dissemination, speed limit information, weather information, accident notification, congestion notification, surface condition notification), co-operative driving assistance systems (driver alert, blind crossing assistance, highway entrance and lane merging co-ordination, traffic lights coordination, emergency vehicle priority co-ordination, eco-driving assistance), in-car navigation and guidance systems including route optimization (based on real-time traffic info) and location based services (such as closest gas station, available parking spot or other point-of-interest), in-car infotainment (movie/music download, multiplayer games), fleet management systems, internet access for the passengers, mobile office, electronic toll collection, drive through payments, wireless vehicle diagnostics and software updates, public transportation information systems, etc. Another suggested application of VANETs is to provide an alternative and flexible communication network in a disaster scenario when infrastructure networks are destroyed. The ultimate vision of ITS is the fully autonomous vehicle that drives itself equally well or even better than when driven by a human driver. Toward this goal, DARPA ran three competitions for autonomous vehicles, two of them in the desert (DARPA Grand Challenge) and one in an urban setting (DARPA Urban Challenge) [40]. Although these contests focused on robot-cars working individually to find their way to the final destination, while avoiding obstacles and other cars and obeying traffic laws, it is believed that by adding V2V and V2R wireless communications, cars will perform even better.

A large number of research projects and other initiatives have been undertaken in the last few years in the area of ITS and vehicular communications. Some indicative European research projects are (see [41] for a comprehensive overview) DIATS, CHAUFFEUR-1 and -2, CarTALK 2000, DRIVE (Dynamic Radio for IP-Services in Vehicular Environments), overDRiVE (Spectrum Efficient Uni- and Multicast Services over Dynamic Multi-Radio Networks in Vehicular Environments), PReVENT, GST (Global System for Telematics), SeVeCom, COMeSafety, COOPERS (Co-operative Systems for Intelligent Road Safety), CVIS (Co-operative Vehicle Infrastructure Systems), SAFESPOT, national projects FleetNet and NOW (Network On Wheels) in Germany, ISVV in Sweden, CVHS in the UK and others. Some EU bodies involved in research and development of ITS are, the Intelligent Car Initiative, ITS Europe, the Car2Car Communication Consortium, the E-Safety forum, ERTICO and IMET.

Automotive telematics enabled by vehicular communications and networks have come a long away towards demonstrable applications and even protocol standards and commercial products. The automotive environment is quite challenging for wireless communications and vehicular networks (at all layers of the network protocol stack) due to vehicle mobility which causes rapid fluctuations to the channel, sudden network topology changes, very short uplink times, network disconnections and network security and privacy concerns. Additionally, some applications require high penetration, i.e., they need to be running on a high percentage of vehicles and/or roadside locations in order to be effective. Obviously, this will require standardization so that hardware and software components developed by different vendors are interoperable and a long time until this kind of applications are deployed and adopted in our every day lives. Other applications and networking protocols that require the participation of a very large number of vehicles face a scaling problem and need to be designed in a scalable way. A lot of research effort has been devoted to intermittent connectivity networks that support delay tolerant applications. VANETs and Infostation based vehicular networks are prime examples of intermittent connectivity networks. In Infostation based networks, for example, the key idea is to predict the content that an approaching vehicle will require to download, prefetch and cache it at the Infostation so that in the very short time the vehicle is in range, it can associate and authenticate to the Infostation and download the requested content. Regulatory and legal issues are also a concern especially in safety applications were a system malfunction can cause an accident. Such issues involve privacy concerns which are not limited to disclosure of the itinerary of a vehicle but also include communication of traffic violations of a driver to the authorities and car insurance agencies. On the other hand, VANETs are not facing hard energy, memory and computational resources constraints as mobile nodes are placed in vehicles and can be powered up by a vehicle's battery or running engine.

## 2.5 Environmental Risk Management

One of the earliest proposed and deployed applications for Wireless Sensor Networks (WSN) is environmental monitoring ranging from wildlife habitat monitoring to environmental hazards timely detection and management. The key concept behind all these applications is to deploy a WSN in an area of interest in order to collect environmental data that will facilitate the study of wildlife in various ecosystems, provide early warnings for flooding, landslides and volcano eruptions, detect and monitor the spreading of wildfires and optimize the firefighting effort, measure the concentration of water, soil and air pollutants, and assist authorities in planning, organizing and executing evacuation and rescue plans in physical or manmade disasters. All these potential applications are made possible by the development and commercialization of very small size and low cost sensors capable of measuring environmental parameters, performing local processing, communicating wirelessly with their short-range neighbors, form networks and eventually transmit useful information through this network to a central location (known as information sink) for further processing, storage and human interaction.

Although some initial pilot projects which required a relatively small number of nodes manually installed in the field (such as bird nests habitat monitoring in the Great Duck Island sensor network project [42]) were successful, initial ambitious plans for throwing a very large number of sensors in a vast area and expect them to self-organize in a WSN and monitor that area met with practical issues. For example in a wildfire monitoring application, throwing sensor nodes from a helicopter in a dense and difficult to reach forest area will probably result into a large percentage of them ending up in locations and positions were they cannot establish a communication link with any other node. Even if nodes are manually attached on trees, dense vegetation disrupts wireless communication in the frequency bands used by most WSN wireless standards (Zigbee, WiFi, etc.) and makes only very short range communication (less than 10m) possible. With such a small communication range, not only the cost of the required sensors to cover a medium size forest becomes substantial but also the effort and cost required to place the nodes in suitable positions is prohibiting. Another important issue is powering up these nodes without the need for battery replacement. Substantial research effort has been devoted to both reduce the power requirements of wireless sensors operation by developing energy efficient protocols in all layers of the protocol stack and to provide sustainable energy resources to sensors (such as by using solar panels, fuel cells, harvesting the energy of micro-vibrations or small temperature differences, etc.). Finally, very rapidly spreading forest fires pose a design challenge in developing a WSN that can detect and track the spreading of the fire and manage to send this information to the sink despite the fact that its own nodes will be one after the other burned by the fire. Despite all these issues, research in this field is ongoing and researchers are hopeful that in the future WSN will be able to provide solutions to some very important and challenging problems in environmental monitoring and risk management. Recently concluded and ongoing EU funded projects on environmental monitoring include WINSOC [43], SANY [44], SCIER [45], MOBESENS [46] and HydroNet [47].

The severe power limitations of sensor nodes are a major concern not only in environmental applications but in all applications in which sensors need to operate unattended and far from abundant power sources for a long time. It is well known that in terms of energy consumption, communication is much more expensive than computation [transmission cost ~100 nJ/bit vs. computation cost ~1 pJ/instruction (HW) or 1 nJ/instruction (SW)]. For this reason, in-network information processing, aggregation, averaging and compression can go a long way regarding reducing power consumption by transmitting only important information to the gateway/sink. It is very important to understand that a WSN is not a mere communication network but an event- and application-driven, data centric and task oriented network closely related to the physical world. This realization has profound implications on the way sensor nodes and WSNs are designed, built, simulated, optimized, deployed, tested and maintained. In many cases, WSN applications are distributed programs aiming at taking optimal distributed decisions about the occurrence and location of an event or perform parameter estimation and multiple hypotheses testing. Compared to a centralized approach, a distributed algorithm has the benefit of avoiding the single point of failure problem and can potentially be more efficient in terms of the amount of data that need to be transmitted over wireless links. Scalability is another important concern in the design of WSNs consisting of hundreds or thousands of nodes and used to monitor large areas. Finally, autonomous, unattended operation which requires methods for self-organization, adaptation, and in-field reprogramming or software upgrading is another mandate for WSN in particular for environmental risk management applications.

### 2.6 Mobile and Heterogeneous Sensor Networks

Traditionally, wireless sensor networks were contrasted to MANETs in that sensor nodes are fixed while MANET nodes are by definition mobile. In recent years, the idea of attaching sensors to moving objects (mobile phones, vehicles, UAVs, etc.) has gained a lot of attention. The rational behind this idea is that moving agents can track the phenomenon of interest so that we need to deploy fewer sensors in order to collect data on phenomena of interest. Another reason is that sometimes we are interested in measuring some environmental parameters at the proximity of moving objects. For example, we might want to know air pollutants concentrations not in an entire city but near people with respiratory conditions. In this case we can attach air pollutant sensors as well as other vital signs sensor to members of this particular target group in order to gather, correlate and analyze relevant data.

Many research projects in this area (such as Nokia's SensorPlanet initiative [48], the Urban Sensing research project at UCLA [49], the MetroSense project at Dartmouth College [50] and others) take the people centric approach of attaching sensors to mobile phones. With an installed base of a little less than four billion mobile phones worldwide, many of those with geo-location capabilities and all of those with a wireless connection through which they can send sensed data to a central location, this *participatory sensing* approach provides an easy way to deploy a system that can collect a tremendous amount of data from around the world. Users will be willing to participate in this data gathering process if they have to gain something in return and provided that their anonymity and privacy is guaranteed [52]. For example, they can get early warnings of environmental hazards such as toxic or radioactive spill offs. The availability of a dense grid of sensors has the added benefit that we can use less accurate (and consequently less expensive) sensors and take the average of their readings to make an equally good estimate of the measured quantity as in the case of employing one very sophisticated and accurate sensor. Mobile phones or other personal electronic devices (laptops, PDAs, etc.) have also been proposed to play the role of data collectors from fixed sensor nodes. In this setup non-expensive sensor nodes are equipped with short range wireless transceivers. They collect and temporarily store sensed data until a mobile phone comes into range and then send all stored data to this phone. The phone is then responsible to forward the data to some central location for further analysis and permanent storage. This way, mixed sensor networks that consist of ordinary fixed sensors and mobile sensors are formed. Another suggestion is to attach sensors to vehicles to form a Vehicular Sensor Network (VSN) as in the CarTel project at MIT [53] and the MobEyes project at UCLA [54].

Proposed applications of Mobile Sensor Networks include urban pollution monitoring at a micro-scale, urban micro-climate investigation, noise intensity mapping, traffic density/congestion monitoring, environmental hazards detection, forensic, accident or crime site investigations, terrorist alerts, public health/epidemiology investigation, and personal environmental impact assessment [51] (e.g., carbon footprint calculation). Collecting such a large and detailed amount of data will allow not only to observe the environment but to gain a deeper understanding of complex phenomena and make better designs of human activities. For example, by analyzing the car emissions pollutants concentrations in an urban area, the environmental impact of new road construction and traffic arrangements can be understood and optimized.

Collecting such a huge amount of information by fixed and mobile sensors creates issues with efficient handling, filtering, sending through the network, storing, discovering and retrieving it in a centralized or distributed manner and making it available through the web to a broad community of users. A lot of effort has been devoted in data stream processing, continuous queries, database schemas and XML representations for sensor data. The goal of the Sensor Web Enablement (SWE) [55] activity of the Open Geospatial Consortium is to "make all kind of sensors *discoverable*, *accessible* & *controllable* via the www". In this framework, they have proposed SensorML, an XML schema which can be used to define the geo-location, dynamic and observational characteristics of a sensor as well as a group of sensors. Apart from the huge amount of sensors that will be gathering data all over the world, there is also a heterogeneity and interoperability issue. Sensors differ in the physical phenomenon they observe, the parameters they measure, the time granularity of measurements they take, the communication protocols they employ, and many other aspects. In order to connect this great variety of sensors to the Internet, they must be made IP compatible and addressable. To this end, a number of schemes have been proposed including running a small IPv6 stack on each sensor (as in the 6lowpan IETF protocol mentioned in Sect. 2.3) or running an IP proxy at a local sink which collects data from a number of sensors and forwards them to the Internet. In the later case, sensors are not IP compatible and the sink performs protocol translation to enable their integration with the broader Internet.

### 2.7 The Emergence of Digital & Intelligent Cities

The digital revolution that has been taking place for the past two decades propelled by major breakthroughs in the ICT field has brought about deep changes in our way of working and living, as the widespread diffusion of ICT is accompanied by organizational, commercial, and social innovations. A host of innovations ranging from cutting-edge technologies in smart devices and sensor networks, to the emergence of mobile and pervasive computing, and the massive convergence of voice, data and content distribution networks, have changed the way we communicate, travel, live—and even the way that we use, plan, and develop *public space* [56,57]. In today's evolving digital communities, citizens, businesses and governments are relying more and more on information networks to transact their daily business. At the same time, our cities are increasingly moving from a collection of static buildings and infrastructures to dynamic and evolving smart ecosystems known as *Intelligent Cities* [58]. The first step in this transformation has occurred with the proliferation of *Digital Cities* across the globe—integrated service-oriented, computing and communication platforms that simplify public transactions, reduce telecommunication costs, and offer a wide range of user-centric

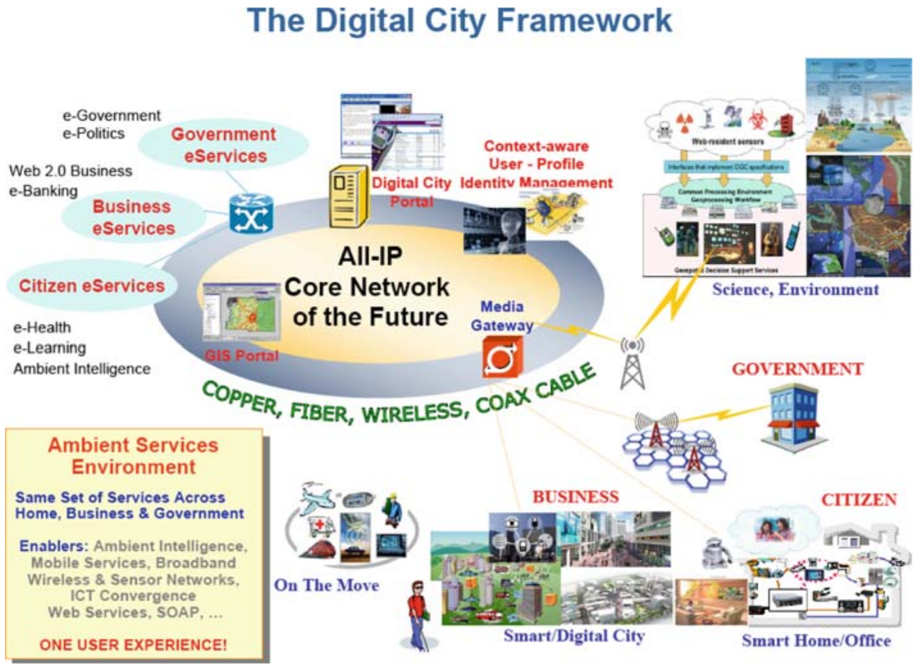

**Fig. 3** Unified service provision framework in a digital city (*source*: [61])

services that meet the everyday needs of residents of urban environments worldwide. A digital city creates an environment for information sharing, collaboration, interoperability and seamless experience for all its inhabitants anytime, anywhere in the city. Building upon the foundations of a digital city infrastructure, an entire city can be designed and programmed to function as an *intelligent/smart-city* ecosystem which is able to acquire and apply knowledge about an environment and its inhabitants in order to improve their experience in that environment [59,60].

The high level architecture of an intelligent city ecosystem, key enabling technologies, and the necessary policy framework for the establishment of digital cities worldwide are discussed in [61]. A Digital City is built around a service oriented infrastructure comprising of broadband information and communication technologies and systems. Woven together these technologies form the *Digital City Fabric* that *connects* and *integrates* the entire community. The intelligent city computing and communications network of the future serves as a platform for multiple services, allowing vendors to offer a plethora of broadband services to engage enterprise and residential users on a voluminous basis due to the social diversity of the city population (see Fig. 3). High bandwidth capacity provided by a combination of both wired (including fiber) and wireless transmission mediums will make connectivity "anytime, anywhere" a reality. Data speeds in the gigabyte and terabyte ranges will carry real-time, multimedia rich data (such as full motion 3D video and immersive environment for tele-presence applications) between both stationary and mobile locations. A single knowledge base, feeding and being fed by numerous subsystems, will serve as the "brain" of the intelligent city. Moreover, Using a Geographic Information System (GIS) to manage data and build spatial relationships in addition to fixed and mobile telephony along with video conferencing—all over IP—will ensure cost effective implementation with improved service functionality.

Intelligent city services will empower city residents by providing 24/7 online access to public services and information from a variety of convenient locations and devices such as public kiosks, home, office, mobile computer, cell phone, PDA. Leveraging the benefits of broadband technology allows a multitude of services to be delivered and offered to all parts of the community in a city environment. Among the intelligent city services offered will be Geographic Information System (GIS) and 'smart maps', Intelligent Transportation System (ITS), e-libraries, e-learning and geospatial query-based address and location finding services.

The Digital City communication infrastructure is meant to be fully flexible and self-organizing utilizing fixed routers, mobile repeaters, a wide range of sensors at various levels monitoring the condition of the city, electronic points of information providing enhanced services to its citizens and a multi transport telecommunications infrastructure that enables the transmission of all the kinds of information. An "*Intelligent environment*" like that can be built on top of a number of existing and emerging systems and networks (an all-IP Fibre-based core network, broadband access networks, community networks, mesh networks, vehicular networks, sensor networks, etc.). Therefore, the basic infrastructure of a smart city is associated with a seamlessly interconnected set of heterogeneous *communication* and *sensor* networks. Broadband communication networks include wireless access networks like Wi-Fi, cellular networks (e.g., 3G, HSDPA, 3G+, LTE and LTE Advanced), WMAN networks such as WiMAX, metropolitan mesh networks [62,63] and their hybrids [64]. In particular, a special architecture of *mesh networks* known as, *community networks* is expected to play a key role in the built up of the digital city fabric. Community networks (such as, municipal Wi-Fi networks) have emerged as a cost-effective solution that provides for ubiquitous access, broadband connectivity, and offers a range of important consumer- and business-related applications to citizens, institutions and companies in a given geographic area [65]. Complementing the access network of the future will be a number of sensor networks comprising of Zigbee nodes, motes and RFID tags to list just a few, which in addition to collecting information from the environment will be capable of providing various services ranging from simple identification of each facility type and location to the activation of a special behavior in case of interaction with an external trigger enabling a city-wide smart space [66,67].

A network architecture that supports the seamless provisioning of multimedia-rich applications over a number of heterogeneous sub-networks is the Next-generation-Network (NGN) adopted by all state-of-the-art and emerging broadband wireless and mobile networks (e.g., WiMAX, 3G+, LTE, etc.). A *Next Generation Network (NGN)* is a packet-based network employing a multitude of QoS-enabled transport technologies, in which service-related functions are independent from underlying transport-related technologies. It supports generalized mobility that will allow consistent and ubiquitous provision of services to its users [68].

A number of technical issues that still need to be addressed in the context of this dynamic heterogeneous communications and distributed computing environment are: Interoperability, Media Independent Handover, Service Discovery, QoS, Transparency (simplicity) to users; Dynamic user/citizen profile; Matching the needs/wants of the user to the available services; Game theoretic approach to satisfy the needs of a larger group of people with possible conflicting needs; Trust, anonymity, misbehavior detection, security, etc.; Computing Platforms & Middleware support for the provisioning of such services on different mobile devices, e.g., cell phones, PDAs, smart-watches, vehicular digital transceivers.

Emerging next generation broadband wireless networks have the potential to realize the longstanding vision of ubiquitous high-speed access to the Internet, offering to the end user *personalized* broadband mobile services anywhere, anytime. The digital city fabric of the future will be able to offer to the city inhabitants network and services ubiquity (i.e., ubiquity of personalized services based on a large diversity of access technologies; location and context awareness; service composition and networking) and global mobility (i.e., services mobility across terminals, technologies and administrative domains; Always Best Connected; Any terminal is your terminal; single sign-on—made easier and faster using bio-identification). This fact may revolutionize society in the 21st century, the way the transistor and the internet did in the 20th century, since the ubiquitous availability of information and communication will change the way we communicate with people and machines. Such a change could help bridge the gap between the physical and virtual worlds accelerating the transition from a digital city to an intelligent city—a city-wide *smart space* offering *ambient enhanced services* to its citizens [69].

Research on digital cities, both physical and virtual ones, is conducted by many individual researchers, e.g., [70], and organizations including: MIT Smart Cities Lab [71], United Nations Public Administration Network (UNPAN), World Foundation for Smart Communities [72], the URENIO Urban & Regional Innovation Research Unit [73], etc. Some representative digital- and intelligent-city projects include the following (see [61] and references within): Crossroads Copenhagen (Denmark), Arabianranta (Helsinki, Finland), Digital Media City (Seoul, Korea), One-north (Singapore), MIT Environs, Northern Ireland Science Park, Digital Mile (Zaragoza, Spain), Sapiens (Florianopolis, Brazil), Salzburg (Austria).

## 3 Theoretical Underpinnings and Research Challenges in the Field of Wireless Communications and Networks

### 3.1 Current Status, Future Growth and Fundamental Limits in Link Capacity

In recent years we have witnessed an exponential increase in wireless access bandwidth that is commercially available to the end user. Gilder's Law [74] predicts a six-fold increase of the available link bit-rate every 1.5 years. It is expected that the need for high throughput will continue to increase in future wireless networks, fired by the rising needs of the mass market in the fields of bandwidth demanding applications in entertainment, multimedia, Intelligent Transport Systems, virtual and augmented reality, pervasive healthcare, emergency response and other applications discussed in Sect. 2.

For point to point wired or wireless communications, Information Theory derives theoretical upper bounds to the achievable link capacity. For an Additive White Gaussian Noise SISO channel the famous Shannon capacity limit states that the maximum attainable bit rate is $\mathrm{C} = \mathrm{W} \log_2 (1 + \mathrm{S/N})$ bps where W is the channel bandwidth and S, N are the transmit power and average noise power respectively. This capacity limit can be substantially increased by employing MIMO systems (multiple antennas at the receiver and transmitter).

As predicted by the Shannon capacity limit, the maximum data rate achieved by various wireless technologies depends primarily on the communication range and available channel bandwidth (the longest the range the higher the signal attenuation which results in a lower received signal power S). In state-of-the-art WWAN technologies (e.g., LTE, WiMAX) the maximum bandwidth efficiency that can be achieved is 1.5–2 bits/s/Hz. Modern WLAN systems using OFDM based basebands combined with MIMO use typically 20–40 MHz bandwidth and can reach up to 300 Mbit/s data rates as indicated in IEEE802.11n. This results in a bandwidth efficiency of up to 7.5 bit/s/Hz. The maximum can be reached only under optimal conditions in a very short range using a frequency band at 2.4 or 5 GHz. Recently, work in the IEEE 802.15.3c Task Group has set as goal to attain 2–6 Gbit/s in short range

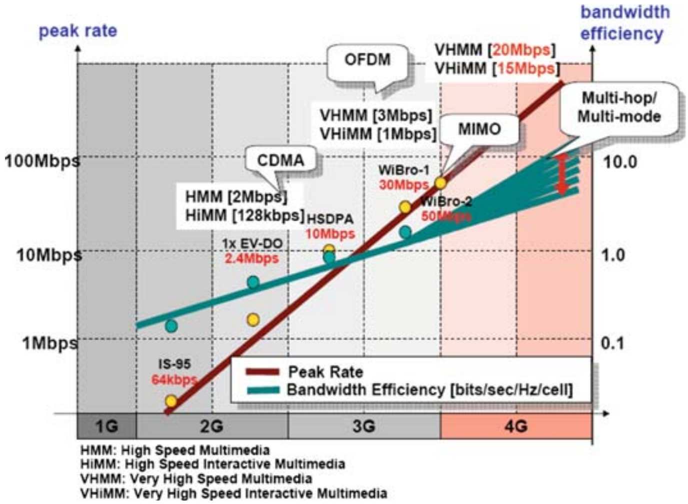

**Fig. 4** The evolution of data rates and bandwidth efficiency in WWAN networks (*source*: Wiselab, Korea [75])

communications in the 60 GHz band. In higher frequency bands wireless systems can use wider channels thus increasing the W factor in Shannon's formula. Unfortunately, the higher the chosen band the lower the achievable efficiency, at least if current concepts (and not innovative ones) are used. Furthermore, high frequencies suffer from higher absorption from obstacles and need line-of-site or near line-of-site propagation to be effective. The evolution of achievable bit rate and bandwidth efficiency in cellular technologies (including some early predicted ranges for 4G systems) is illustrated in Fig. 4. The Figure also depicts the data rate requirements of various services offered over wireless WANs.

Another trend in achieving higher data rates in wireless communications is to lower the transmission range. In cellular systems, this translates in decreasing the size of cells. Currently a lot of hype is generated by the concept of *femtocells*[1] that cover a very small area (e.g., the interior of a house or building), are easily installed by the costumer (plug and play), are integrated in the overall cellular network and offer much higher data rates and QoS (and at a lower power consumption) than the standard macro-cell connections. The decreasing cell size trend in several generations of cellular networks is illustrated in Fig. 5.

## 3.2 Network Capacity Analysis

As explained in the previous subsection, Information Theory derives theoretical upper bounds to the achievable link capacity for point to point wired or wireless connections. In wired networks, the capacity of a multi-hop path is equal to the capacity of the link with the lowest capacity in the path, while the capacities of parallel connections are simply summed together to determine the total capacity. However, in wireless networks, transmissions in one link interfere with transmissions in a neighboring link of the same network. Hence, by increasing the transmit power in one link thus increasing its capacity, the interference power to all other links increases thus lowering their capacities. TDMA, FDMA or CDMA

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[1] See 8 articles on femtocells in the September 2009 issue of IEEE Communications Magazine and 3 more articles in the January 2010 issue of the same magazine.

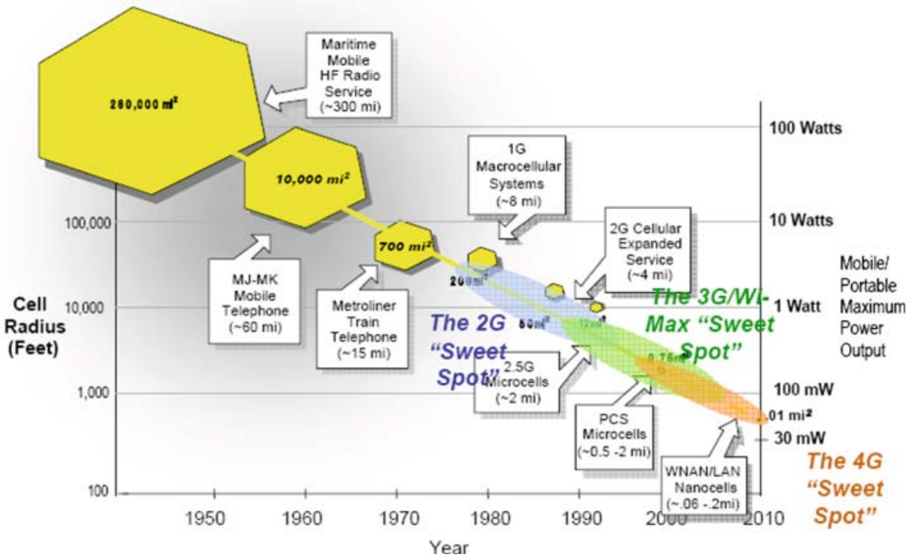

**Fig. 5** The evolution of cell sizes and transmit power in cellular networks (*source*: R.R. Miller, AT&T, IEEE 802.11-05/0173r0 [76])

multiplexing of transmissions in various mutually interfering links can be employed but this reduces the capacity of each link by dividing the available time and bandwidth among a number of interfering links. Furthermore, the use of multi-hop transmissions and the availability of alternative paths from source to destination add many more optimization variables to the problem: given a known set of traffic flows what is the routing of all flows that maximizes the total data rate? Nodes mobility, latency constraints and fairness among different traffic flows constraints further complicate the problem. Finally, cooperative transmission, network coding, MIMO and directional antenna techniques can all boost network capacity but at the same time add new dimensions to an already complex problem. It turns out that a theoretical capacity bound for wireless networks is not known (except when assuming specific current technologies) and remains the "grand challenge" of information theory.

In the last decade, a number of important works have helped to advance the state-of-the-art in the capacity of ad hoc networks question. More specifically, in their seminal paper [77], P. Gupta and P. R. Kumar derived asymptotic bounds for the capacity of fixed wireless ad hoc networks as the number of nodes in the network grows to infinity. Nodes in this network are immobile and randomly placed in a given area. Each node is paired with a random destination node to which it sends data packets either by single-hop or by multi-hop paths. Messages are buffered at nodes while awaiting transmission and sufficiently distant radios transmit concurrently. The main result in [77] shows that the maximum throughput per source-destination (S-D) pair is $O(1/\sqrt{n})$where $n$ is the number of nodes per unit area while a proposed scheduling scheme can achieve a throughput of $\Theta(1/\sqrt{n \log n})$. This means that the per S-D pair throughput tends to zero as $n$ grows to infinity. The reason for this is that as the number of nodes increases, either the per hop transmission range should decrease (and therefore the number of hops between source and destination increase) or the number of interfering transmissions will increase resulting in overall capacity reduction. Although this is an important result, it addresses only the limit case of a very large number of nodes randomly placed in an area, rather than specific practical cases.

In a paper also published in 2000 [78], Ahlswede et al. showed that network coding strictly increases multicast capacity at the expense of added computational complexity. Then, in a 2001 paper [79], M. Grossglauser and D. Tse proved that mobility can drastically increase the capacity of ad hoc wireless networks in which Mobile Nodes (MNs) play the role of data carriers. More specifically, they showed that the average long term throughput per S-D pair can be kept constant as the number of nodes per unit area $n$ increases. The caveat is that, in order to maintain constant throughput, nodes buffering capacity and packet delivery delay will increase unboundedly with the number of nodes (the tradeoff between throughput and delay in MANETs has been further studied in, e.g., [82]). This significant increase in capacity is achieved by limiting the number of hops in each S-D path by using randomly moving MNs as physical data carriers. Fewer hops result in reduced interference with other transmitting MNs thus achieving capacity increase. In their 2001 paper [80] Li et al. addressed a subproblem of the generic MANET capacity problem. They proved that certain traffic patterns and certain topologies scale, e.g., a long chain of carefully spaced fixed nodes has capacity 1/4 of the one-hop sending rate independent of the number of nodes. The following year, P. Gupta and P.R. Kumar showed that successive interference cancellation and multiuser coding schemes increase network capacity per user to a constant factor [81]. Their results apply to a specific class of fixed ad hoc networks and do not consider potential capacity increase by using network coding. Another important result was published in 2006 by X. Lin and N.B. Shroff [83]: a cross-layer design approach is strictly superior in terms of achievable network capacity to a layered approach. However, the optimal scheduling problem when taking into account all optimization variables is very complex and does not necessarily have a polynomial-time solution.

In early 2006, DARPA launched ITMANET (Information Theory for Mobile Ad Hoc Networks) a funding program for the study of the full and unrestricted problem of theoretical capacity limits in MANETs [84]. Two multi-university teams were selected to receive research grants under this program: the Nequit team [85] and the FLoWS team [86]. In a recent "vision paper" [87], the members of the Nequit team argue that some shifts in thinking might be needed in order to overcome what they see as the three key roadblocks for information theory to be successfully applied to decentralized wireless networks: "First, most current capacity results rely on the allowance of unbounded delay and reliability. Second, spatial and timescale decompositions have not yet been developed for optimally modeling the spatial and temporal dynamics of wireless networks. Third, a useful network capacity theory must integrate rather than ignore the important role of overhead messaging and feedback."

In conclusion, the question of theoretical capacity limits for MANETs is still unsolved and attracts the attention and efforts of some of the most renowned researchers in the field of wireless communications and networking. But even if the full problem is never solved, intermediate results in this quest have their own value.

### 3.3 Cognitive Radio and Cognitive Networking

Traditionally, specific regions of the radio spectrum are licensed for personal communications, TV and radio broadcasting, military and government communications, satellite communications, etc., using a static channel assignment policy. This gives exclusive spectrum access to the license owner. In case the license owner does not need to transmit at a certain frequency band and at a certain time this time-frequency resource goes to waste, thus underutilizing the available precious spectrum. The *Cognitive Radio* paradigm has been put forth in order to take advantage of the observation that some parts of the spectrum become increasingly crowded while other parts become underutilized at a specific time and in specific geographic locations [88,89,91]. In its original definition [90], cognitive radio is a way to redefine the use of spectrum licensing so that the available spectrum can be freely used by unlicensed users at anytime without disturbing licensed users. To enable it, cognitive terminals (also known as secondary users) must be allowed to access the spectrum wherever and whenever it is not actively used and without causing any significant interference to other users, whether licensed (also known as primary users) or unlicensed. Three different approaches for dynamic spectrum access by secondary users have been proposed:

1. Spectrum underlay: In this approach secondary users limit their transmit power to guarantee that the aggregate interference at any primary receiver is below its noise floor, and hence, do not cause any significant interference to primary users. Obviously, this approach severely constrains the transmit power of secondary users.
2. Spectrum interweave, also known as *Opportunistic Spectrum Access* (OSA) and previously known as spectrum overlay: In this approach, secondary users will identify the unused spectrum or "spectrum white spaces" (by using sensing algorithms) in which non-disruptive transmission becomes feasible (detect & avoid strategy).
3. Spectrum overlay: In this approach secondary transmitters transmit concurrently with primary transmitters but have some a priori knowledge of the primary users' message and/or codebook and exploit this knowledge to cancel/mitigate the interference at primary and cognitive receivers. Obviously, the big issue in this approach is how the secondary users can obtain this knowledge in real time.

Overall, there are several technical and regulatory issues that need to be addressed before cognitive radio can become a practical technology. Obviously, established "legacy" operators that hold exclusive license rights are reluctant to share this spectrum with new entrants ("small players") that could greatly benefit from the co-existence of primary and secondary users. In the most popular OSA approach, secondary terminals need to quickly scan a wide portion of the usable spectrum in order to identify white spaces. Activity detection becomes challenging as low SNR situations can be expected, due to possible shadowing effects and "hidden node" problems [92,93]. A lot of research effort has been devoted into developing methods for fast and efficient spectrum sensing that employs standard, not-too-expensive hardware, and meets FCC's regulatory requirements, but the state-of-the-art is still not commercially viable. User mobility and intermittent spectrum usage by primary users are also complicating the problem of spectrum sensing. Secondary users must be able to detect primary users trying to access the channel while they are transmitting and immediately abort their transmission. Apart from being able to sense the spectrum for white spaces, OSA devices must be able to communicate in different frequency bands possibly by using different protocols. This may be achieved by the use of *Software Defined Radio* (SDR) technology [94]—transceivers whose communication functions are mapped onto programs running on suitable processors. Another critical problem in cognitive radio is the efficient coordination between secondary transmitters and intended receivers in order to use the same white space and between secondary transmitters in order to fairly share the available spectrum. A complete MAC solution for WiFi-like networking on top of UHF white spaces is proposed in [95].

In Sect. 2, many of the discussed applications required large scale, unattended and flexible wireless networks that can not only perform communication tasks but also process information at a high-semantic level, plan, decide/reason, act and learn. In other words, a network that possesses cognitive abilities commonly referred to as a *cognitive network* or a *cognitive networked system*. A cognitive networked system is able to perceive current network conditions, and then plan, decide and act on those conditions. The network can learn from these adaptations and use them to make future decisions, all while taking into account end-to-end goals. A cognitive networked system:

- can reason, using substantial amounts of appropriately represented knowledge;
- can learn from its experience so that it performs better tomorrow than it did today;
- can explain itself and be told what to do;
- can be aware of its own capabilities and reflect on its own behavior;
- can respond robustly to surprising events and conditions.

A cognitive network differs from a network of nodes with cognitive radios due to: end-to-end scope of goals, support for heterogeneity (wired/wireless nodes), scale of cooperative elements (spanning multiple layers and the entire network), and higher complexity due to a higher number of tunable parameters (Software Defined Radio, software adaptable network, adaptive applications, reprogrammable nodes). For example, in a cognitive network, a different wireless multi-hop route (and not only a different frequency band and time to transmit) can be selected in order to optimize a diverse set of optimization criteria such as data rate, delay, monetary cost, policy requirements, impact to other nodes and users.

In cases were cognitive network nodes are cheap, error-prone devices with limited computational, storage and energy resources (such as sensors in WSNs) implementing complex cognitive tasks is a real challenge. It is very difficult for these nodes to process and store big amounts of information and then infer/reason based on this information. New ways of performing complex tasks in a distributed way need to be devised, possibly inspired by biological cognitive systems (e.g., by mimicking the way the human brain performs complex tasks by the cooperation of millions of neurons each one of which performs a simple function).

Recognizing the importance of research and standardization in the field of cognitive radio and cognitive networks, IEEE has recently formed the Technical Committee on Cognitive Networks (TCCN) [96]. US federal government is also actively supporting research in this field by programs such as DARPA XG and NSF NeTS ProWiN.

### 3.4 WSN Programming and In-Field Reprogramming/Re-configuration

When developing an application that will run in a WSN, the developer needs to write code that will run at each node on top of the node-level OS (e.g., TinyOS) then create an executable image that must be “flashed” on each device separately, get initialized and start running. Writing code for each device separately so that all networked devices perform the required distributed functionality is a tedious task. Ideally, a developer should be able to explain the desired system behaviour in some high-level formal way and the system in turn, should have the embedded intelligence to parse the instructions of the high-level description and task individual nodes accordingly in order to perform the described functionality in a distributed fashion. In addition wireless sensor networks consist of hundreds or even thousands of nodes which are deployed in sometimes difficult to access locations and need to run unattended for long periods of time. In these cases, reprogramming the sensors needs to be performed in-field through the connections provided by the WSN itself. In-field reprogrammability of sensor networks has been identified as an indispensable requirement for their efficient deployment and lifecycle operation in large scale applications. However, wireless sensor networks characteristics such as wireless link and node unreliability and resource constraints make sensor network reprogramming a challenging task. A wide range of techniques for in-field reprogramming of WSN have been proposed in the literature and incorporated into the designs of many sensor nodes (see [97,98] and references within). In order to reprogram a WSN in field, the new code has to be distributed to the nodes over the wireless network and the installation and launching of the new code (and removal of the old code) on individual nodes has to be performed automatically by the nodes themselves.

In-field reprogramming of WSN consists of altering the software running on one or more nodes in the WSN without removing them from their operational position. Software updates on a sensor node could potentially concern any part of the code running on this node including: an application or application module, a driver for some device (sensor, network interface, etc.), a networking protocol, the operating system or the middleware which runs on top of it. The new code might be a new version of current code, a slight modification/tuning of software parameters or an entirely new module or program that needs to be added on top of the current code.

In-field reprogramming requires delivering the new code to the node(s) that need(s) to be reprogrammed and installing this code to the appropriate node(s), possibly replacing the current code. Many designing issues need to be addressed for both problems. For the problem of code dissemination: deciding to which nodes and at what time the code needs to be installed; efficiently broadcasting, multicasting or unicasting the code to selected nodes; authenticating and verifying the distributed code; minimizing the amount of data to be sent over the network by using compression, differential updates and appropriate programming paradigms; and efficiently store recurrent code (e.g., by using mobile agents or more generally mobile code). For the problem of new code installation: design of a runtime loader and runtime linker of the module; loading of the code in the main memory (RAM) from EEPROM or Flash; potential need for writing in the flash, modifying the boot loader and rebooting of the node in cases where the OS is monolithic and reinstallation of the complete OS is required; stopping the running application for a period of time (freezing); taking care of the memory address space and manage existing data in the memory, so that the new code can also use them; and finally unloading existing modules and loading the new ones if the OS is modular and supports dynamic module loading.

Many approaches exist to sensor programming and reprogramming. Most of them involve the use of some middleware [99] whose purpose is to support the development, maintenance, deployment and execution of sensing-based applications. The existing methodologies for WSN middleware design can be grouped into the following four categories:

*Virtual Machine-oriented*: It lets developers write applications in separate, small modules. The system injects and distributes the modules through the network using tailored algorithms, such as overall energy consumption and resource use are minimized. The VM then interprets the modules. This approach mainly suffers from the overhead that the VM instructions introduce. Examples are Mate [100], Magnet OS [101] and SensaWare [102].

*Database-inspired*: The whole network is seen as a distributed database system. User issues queries through an easy-to-understand interface, that most of the time is an extended set of SQL-like commands. This approach provides only approximate results and lacks the support of real time applications that need the detection of spatio-temporal relationships between events. Examples are Cougar [103], TinyDB [104] and SINA [105].

*Mobile-Agents based*: In this approach, applications are as modular as possible to facilitate their injection as programs and distribution through the network using mobile code. These programs can collect local sensor data, can statefully migrate or copy themselves to other nodes, and can communicate with such remote copies. Transmitting small modules consumes considerably less energy than transmitting a whole application. Usually, in such approaches, the nature of the application code makes it difficult to support hardware heterogeneity. Examples here are Impala [106] and Agilla [107].

*Application driven*: Middleware is designed in such a way that it can reach and interact with the network protocol stack, giving the opportunity to programmers to tune the network on the basis of the requirements of the applications. This way applications control the network operation, providing a QoS advantage in comparison with other middleware approaches. A drawback of the application-driven middleware is that the resulting software is tightly coupled with the specific application, and therefore it cannot be used as a general-purpose framework. A representative example is Milan [108].

### 3.5 Biology Inspired Designs

Despite all the computational power and memory capacity of present day digital computers there are still several tasks that the human mind can accomplish in a better and faster way. Scientists are only beginning to understand the exact mechanisms used by the human brain to perform these cognitive tasks. Other biological agents ranging from bacteria and cells to insect colonies and organs solve complex problems effectively by essentially simple designs. Researchers have been fascinated by such biological systems and are trying to solve a wide range of difficult and complex problems by biology inspired designs. There are many such examples in a wide range of technological fields including material science, aeronautics, computer security, optimization, artificial intelligence, robotics, etc. Wireless communications between nano-devices (discussed in Sect. 2.2) are entirely inspired by molecular based communication between biological agents (including cells and whole organisms). In this subsection we discuss some other examples of biology inspired designs in large scale wireless networks.

The key innovative technical idea explored in the WINSOC project [43] was inspired by the role of self-synchronization in biological systems. Take for example the mechanism that results in the human heart sustaining a relatively constant heart beat (within a safe range): a single natural pacemaker cell has a life cycle much smaller than the average human being lifetime and is characterized by limited individual reliability and precision. Nevertheless, a population of mutually coupled pacemaker cells gives rise to a very stable and reliable system. In the same way, a collection of non-expensive sensors which exhibit limited reliability (some of the nodes or communication links in the networks might fail permanently or for a random amount of time) and limited precision in measuring a physical parameter, could be coupled together to form a very reliable system. More importantly, this can be achieved by the exchange of very little local information. During the course of the project this idea has been demonstrated to work for finding local averages of a scalar parameter as well as determining the rate of change in their values.

Another example is bio-inspired multi-agent data harvesting [109] with applications in vehicular sensor network in which agent vehicles (e.g., police cars) move around and harvest meta-data about sensed information from regular VSN-enabled vehicles. In such a setting, VSN nodes collect massive amounts of data such as video which is impossible to deliver in their entirety to a central location for further processing. It is also hard to make a-priori filtering of important data because nobody can anticipate which data will be useful in future investigations. Thus, data are preprocessed, tagged, stored locally and subsequently harvested by a number of moving agents with come into a wireless short range communications distance of the data holder. The problem here is to design a completely decentralized algorithm to coordinate the movement of agents so that they can efficiently collect all data of interest. The proposed solution is based on three biological phenomena: (i) *foraging* (i.e., searching for good food sources) behavior of E.coli bacteria, (ii) *Lévy walk* behavior of many biological organisms and groups and (iii)*stigmetry* found in ants and other social insects that signal each other by using various types of pheromones. The combined use of all the above techniques result in mobile agents moving towards and staying in areas with newly created data of interest, randomly hop into other areas of exploration in a Lévy walk pattern and avoid useless concentration of agents in the same area. It is shown that the proposed algorithm performs better than other decentralized harvesting strategies in a variety of scenarios and a wide operation parameter range.

### 3.6 Physics Inspired Designs

As in biology inspired designs, physics inspired designs are also based on the belief that "nature knows best". Physics inspired designs use methods that are well known in Physics (such as the macroscopic or statistical view of a complex system) or analogies to physical phenomena and problems for which a known solution exists in order to gain intuition and avoid solving a very similar problem again.

For example, the problem of optimally placing the minimum required number of wireless nodes used for relaying sensed data from source to sink in a WSN is way too complicated to be solved without proper abstractions. A macroscopic approach taken in [110] uses macroscopic quantities (node density, data creation density, etc.) and their relationships to arrive to a problem formulation that is analogous to electrostatics. The results of solving this problem using this approach are not as detailed as with the standard microscopic approach, but are detailed enough to remain useful and can be obtained very quickly by solving a small number of standard equations.

Consider now the problem of finding the optimal-cost source-destination path through a 2-D network of randomly placed nodes when the cost of one hop $c(r)$ is analogous to the square of the hop length $r$. In this case, the lowest cost trajectory does not track the straight line connecting source and destination but is attracted by areas of higher node density [111]. This is analogous to the path taken by a ray of light travelling through matter with the index of refraction $n(r)$ playing the role of the cost function $c(r)$. Thus, the rich body of mathematical results that already exists in optics can be easily adapted and applied to this problem [112].

## 4 Conclusions

Despite the amazing development of wired and wireless telecommunications technologies in the last few decades and the deep impact these developments had in our societies and every day lives, the Internet revolution is far from over. In this paper we have described some of the main fields and application areas that will be transformed by recent and upcoming innovations in wireless communication technologies. The increasing dependency of society on the Internet is transforming it from an "information service" to a "critical infrastructure". As technology advances increase the capacity and pervasiveness of wireless networking, new classes of applications become possible which in turn require higher capacities and push the technological developments even further. In this upward spiral we often hear about the fundamental limitations of the current internet architecture. It is a matter of serious debate if the Internet can continue growing based on small incremental enhancements or a disruptive redesign, an Internet 2.0, is now needed.

The disruptive technologies presented in this paper have reached a different state of maturity; some are currently becoming commercial realities while others are still in the stage of basic research. Key challenges for wireless network research stem from complexity, large scale, the need for self-organization, cognition and learning, and the need to support critical activities over unreliable wireless connections. Many of the emerging technologies and applications are of an interdisciplinary nature and require the collaboration of scientists and engineers from many different fields. Interdisciplinary collaboration is often leading to surprising results and providing simple solutions to long-time standing problems that are just viewed from a different angle.

As in many emerging fields, a lot of recent results are not yet perfectly understood by the research community and they are based on the intuition and inspiration of some talented individuals. As complex systems become too complex for a human to grasp, the need for simplifying abstractions and analogies is becoming obvious. For the same reasons and given the life critical applications that some of these systems are built to support, robust and scientifically rigorous methodologies for large networks and distributed systems development and validation are required. To this end, the ongoing and future creation of new tailor-made development and simulation tools and new programming paradigms will allow the co-design and development of sensor nodes, in-network processing schemes and event-driven, data-centric applications.

It is most certainly very hard to predict the future development of any technology. The purpose of this paper was not to predict the long term evolution of wireless technologies and applications. It is also impossible to cover every topic, project and important result in this very broad and vibrant field. We have rather tried to give a general overview of current research efforts and identify technical challenges and major obstacles to the way forward. We hope that we have given the reader a good starting point for further investigation of the numerous exciting ideas and research directions discussed in this paper.

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