# Hop-by-Hop Toward Future Mobile Broadband IP

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## ABSTRACT

We try to give some perspectives on likely trends in future wireless broadband networking. The treatment is an exploration of some technologies; due to the requirement to cover the topic from a broad perspective, it is not possible to go into technical details. We review current developments toward future mobile broadband networks, and then present the 4G paradigm of trying to combine heterogeneous networks, both cellular wireless hotspots and *sensor networks*, together with Internet protocols. We show how different networks play their own roles in the emerging infrastructure so that we can hop by hop wave the broadband network from mobile devices toward the fiber optic core network.


## INTRODUCTION

This article focuses on the question of where wireless broadband internetworking and related technologies might be headed. We do not claim it to be a balanced technology-based roadmap. Instead, it is meant to pose maybe even slightly controversial questions and point out research possibilities that lay ahead. When we started to work on this article, some of us had already been highly influenced by two recent and excellent treatments, one by Raymond Steele on the future of radio communications [1] and another by David Farber on the future of internetworking [2]. Readers can find more food for thought in those papers.

We focus on wireless communications, and leave out discussion of broadband fiber optic and photonic communications. However, we point out that fiber optic infrastructure is becoming more pervasive, leading to a society where broadband connectivity is available always when one is stationary and most of the time when one is moving. Ubiquitous broadband fixed communications infrastructure will most probably dramatically challenge some simple current assumptions on the benefits and attractiveness of mobile and wireless broadband multimedia. Almost paradoxically, photonic communications and fiber optics are at the same time enhancing and slowing down the wireless Internet business domain. Mainly, we claim that it is driving wireless broadband communications further at an increasing pace, since it will enable fast and cheap core network communications even for wireless picocells.

In this article we progress from near future challenges and trends, where the research community has actual results and knowledge, toward the more distant future, our description of which one may choose to categorize as bad science fiction.

## THE NEAR FUTURE: HETEROGENEOUS NETWORKS

### SETTING A SCENE

One could argue that the near future, the next few years, looks obvious, because most of industry and academia seem to agree on the research agenda and vision. In long-term research too strong consensus and momentum could potentially lead to a "network inventors" dilemma; there is danger of concentrating too much on incremental development of existing paradigms and successful networks, and forgetting innovative and distributive research.

Nevertheless, during the last couple of years the combination of Internet technologies and mobile communications has been successfully considered the major vehicle toward the next phase of telecommunications networks. Especially in the case of cellular network integration, this is typically referred as *all-IP networking*. Traditionally data-communications-driven Internet and voice-dominated mobile communications were separate disciplines, both enjoying exponential growth. If we define this as a first step of the convergence, we can argue that most of the basic technology building blocks already exist for it. The basic framework for wireless Internet is already reasonably well understood in both mobile radio (cellular) systems and more open wireless LANs (WLANs). However, the *practical* integration task between traditional (cellular) radio systems and TCP/IP-based architectures remains formidable with all its details and performance tuning. A lot of work is needed before transparent all-IP networking becomes reality (caveat emptor: there is no universally accepted exact definition for all-IP networking).

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Although the near-term research and development (R&D) seems quite straightforward, economic and business environment uncertainties make it hard to predict any precise timing. It is clear that cellular networks will continue to improve in terms of capacity, services, and coverage. The most urgent development is enabling heterogeneous networking, including support for vertical handovers (described by several authors), seamless roaming, and micromobility with IP. A number of companies are active with early products in this field. We also believe that in the case of *wireless* quality of service (QoS), we are becoming more pragmatic. Some issues will be solved at the application layer, and we will have to accept inherent limits of unreliable wireless channels.

We will become softer and softer in the future. Software-defined radio (SDR) technology [3] will become available, and reconfiguration time will not be an issue. There is a long research road ahead before this is a reality. Not only will wireless terminals and base stations become SDR-based; the core backbone network will also gain more adaptivity and reconfigurability. The proportion of software in telecommunications systems will increase everywhere. Terminals, phones, routers, and other devices will be able to process and hold more and more programs. Mitola [4] has noted that the ultimate terminal is not "just" a software radio, but something called a *cognitive radio*. It will integrate SDR and ubiquitous context sensitivity paradigms so that wireless terminals can automatically adapt to the environment, requirements, and network. So maybe our terminal and services will also adapt to our moods. The salesperson shall not be calling us when our terminal informs the network that we are in a particularly cranky mood. The ultimate progression of technology like this might not be "just" cognitive radios, but instead something we would like to call *cognitive networks*. Context sensitivity with the possibility to use artificial intelligence (AI) based methods in networks might become as interesting as the cognitive radios outlined by Mitola.

## WLANS, 3G AND 4G

WLANs have started to become more popular, not only within companies and homes, but also as a public hotspot technology. The reasons for the popularity of IEEE802.11-based networks are simple: the technology is cheap; for upper layers and applications it performs just as "wireless Ethernet"; and as unlicensed radio technology it is easy to deploy. It is also the only widely available wireless technology to quickly build broadband wireless networks. The development of WLAN technology from early 1 and 2 Mb/s models to present-day direct sequence spread spectrum (DSSS) and orthogonal frequency-division multiplexing (OFDM)-based systems up to 54 Mb/s has been quite rapid, and work done toward future extensions on upper layers, QoS, and innovative new physical layer technologies is still going on (e.g., with IEEE802.11e and .11i, and in a study group for next-generation, .11n).

There have occasionally been suggestions that third-generation (3G) cellular technology, which has been promising at first 384 kb/s and later up to 2 Mb/s connections to a user, is not going to break through commercially because of the emergence of WLANs. However, it is too early and drastic to predict that. It is clear that 3G has problems. It has not reached the quick and strong global success most of its ardent supporters claimed it would, and it is hard to predict its commercial progress; but 3G systems will emerge. There was perhaps unavoidable hype surrounding 3G, and we should not make the same mistake with WLAN hotspots. WLANs will be an inevitable and important part of the future wireless and mobile broadband infrastructure. However, we also need large-scale cellular networks to support high-velocity mobility and provide geographical coverage. One also should not overemphasize only raw radio bit rates, as it is well known that the actual application bit rates with WLANs are lower (e.g., with TCP the maximum data rate would be about 6.1 Mb/s in 11 Mb/s mode in ideal conditions); and of course, the capacity is shared between users. The overall aggregate capacity of cellular technologies is also high. The simplified battle between the "best technologies" does not make sense, since different technologies have their optimal usage in different places. In Table 1 we summarize some existing and emerging wireless technologies. This positioning of technologies raises the issue of the fourth generation (4G).

At the moment, 4G is a hot topic. The term is still vague, as a number of different interpretations exist. Some people see it as a new radio interface in the traditional movement from 3G to a new "full" standard, which presumably would provide at least higher data rates and better adaptivity. Another often used interpretation refers to heterogeneous (integrated, IP-enabled) wireless networks. Probably the truth is a combination of both, as the future hierarchical and heterogeneous overlay network infrastructure will also *definitely require* new air interfaces — and enhanced adaptivity — in order to provide better scalability, QoS, and wireless capabilities.

A safe bet is to see 4G as a system of systems that brings in standardized capabilities and technologies to make composable and autoconfigurable networks. There is a lot of interesting research done in this direction; one new large initiative is the Ambient Networks integrated project funded in part by the European Union 6th Framework Research Program. However, although combination of networks is key, the actual deployed 4G networks will also include new radio technologies; most probably, up to 1 Gb/s wireless will be possible in shortrange, and new innovations, especially in the area of MIMO and UWB, will be used to the fullest extent.

It is now clear that a *single* global 3G cellular standard will not materialize; it might even be doubtful if any such cellular super standard is globally needed in the far future *if* SDR technology can provide harmonization. The core cellular technology will be based on 3G,including Universal Mobile Telecommunications System (UMTS) and code-division multiple access 2000 (cdma2000); Global System for Mobile Communications (GSM) evolutions such as General Packet Radio Service (GPRS) and Enhanced Data for GSM Evolution (EDGE) will play an important role. Even before full SDR capability,

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*The proliferation of cheap access technologies will drive the increase of different community networks, and has lead to the emergence of new operators, especially in the area of WLAN access.*

| Network | Standard | Radio basic rate | Frequency band | Mobility |
|---|---|---|---|---|
| WLAN | IEEE802.11b | 1, 2, 5.5, 11 Mb/s | ISM 2.4 GHz | Low |
| | IEEE802.11a | Up to 54 Mb/s | ISM/UNI 5 GHz | Low |
| | IEEE802.11g | Up to 54 Mb/s | ISM 2.4 GHz | Low |
| Bluetooth | IEEE802.15.1 | 1 Mb/s | ISM 2.4 GHz | Low |
| WMAN | IEEE802.16 | 134 Mb/s | 10–66 GHz | N/A |
| | IEEE802.16a | 70 Mb/s | 2–11 GHz | N/A |
| 2G | GSM | 9.6/57.6 kb/s | 900/1800/1900 MHz | High |
| | GPRS | 115 kb/s | | High |
| | EDGE | 384 kb/s | | High |
| 3G | UMTS/WCDMA | Up to 2 Mb/s | 1900–2025 MHz | High |
| UWB | IEEE802.15.3a (?) or de facto | Potentially up to 400 Mb/s | 3.1–10.6 GHz (FCC) | N/A |
| Sensors, UbiComp | IEEE802.15.4 and proprietary systems | 5–200 kb/s | 433, 866, 916 MHz 2,4 GHz (ISM) | N/A or low |
| Next-generation WLANs | | Up to 1 Gb/s (indoor), 150–250 Mb/s (outdoor) | — | Low |

**Table 1.** *Various existing and emerging wireless technologies.*

early versions of software radios can be used to provide multimode terminal technology for users; of course, multimode terminals are already available. The key issue in heterogeneous and composable networking is to use all different aspects and capabilities of networks to provide a good user experience.

In fact, cellular networks such as existing 2.5G and 3G networks have excellent global reach and good customer management (most notably billing and authentication) functionalities. Many key players in the field, among them Ericsson and Nokia, have lately demonstrated cooperation and vertical handover capabilities between WLAN, 3G, and 2G networks. The interworking architecture between WLANs and 3G/2G systems could provide fast deployment for global roaming and billing [5]. Hence, the controversy between 3G against WLAN is partially already being tackled, and the 3G Partnership Project (3GPP) is working on interoperability.

There is still a need to provide better harmonization of WLAN and cellular network interfaces with operating systems and other higher-layer software. The present very heterogeneous situation is slowing down some interesting work from application developers who have no interest in developing different versions of the same software base for all the different wireless access technologies. We expect that some universal interfaces and access wrapping methods will emerge in the near future to make this situation easier.

### Community and Ad Hoc Networks

The proliferation of cheap access technologies will drive the increase of different community networks, and has led to the emergence of new operators, especially in the area of WLAN access. This is also leading to challenges to manage scarce resources, and provide efficient spectrum cooperation even for the industrial, scientific, and medical (ISM) bands. Intensive work in this field has started, but more is required in order to provide maximal use of resources and avoid overcrowded spectra.

Ad hoc (or infrastructureless) networking has been studied quite intensively, and mobile ad hoc network (MANET) standardization activities have been progressing in the area of routing. Ad hoc research is finally starting to bear real fruit for users and business. However, the real-life requirements and applications for massive ad hoc networking are still elusive. There are many good visions for using pure ad hoc networking in military, government, and emergency contexts, but fewer for consumer applications; many civilian applications, especially in the peer-to-peer context, do not seem to require multihop communication capability. Recently issues of how to integrate wireless ad hoc islands with other wireless networks and the core IP network have gained momentum [6]. Ad hoc networking is one area that is rapidly reaching the threshold of commercial development. It will be very interesting to see the full complement of ad hoc applications.

Perhaps the greatest underlying question in ad hoc networking lies not just in how to provide (high) mobility ad hoc multihop networking capability; at least as important is the issue of how to provide (temporary) zero-configuration networks. Obviously, routing protocols are only a partial solution to this problem. Providing better solutions to automated zero-configuration networking and network management through protocols and software agents will be very important in the future. Autoconfigurability seems to be, in the short term, a more tempting possibility for consumer market products than massive high-mobility ad hoc networking.

Combining the community networking technologies developed for WLANs, ad hoc routing technologies and probably mobile IP support provides the possibility to build multihop wireless mesh networks. There has been increasing interest in this area, and although some commercial early attempts have not led to large-scale deployment, there is still a strong drive to enhance mesh network capabilities.

Mesh networking combined with end user mobility is probably an important key ingredient to provide extensive and ubiquitous wireless broadband access for everyone. Especially in city areas, the wireless mesh network overlay structure can be used to feed information toward local ad hoc and peer to peer networks based, for example, on WLAN or UWB technologies.

## THE LAST STEP: UBIQUITY AND SENSORS

Pervasive and ubiquitous computing has already emerged, or perhaps one should say had a renaissance, as a highly popular R&D topic. This is closely related to the increased interest in embedded networks [7] and short-range wireless communications. Different ubiquitous networks, including wireless personal area networks (WPANs) and wireless personal networks (WPNs), will emerge to provide first niche applications and later more generic services for users. This trend will also include different low-power sensor networks in both the industrial and home contexts. First, ubiquitous context-sensitive applications could be hard-wired to provide certain well-defined functionalities. As pointed out by Erickson [8], generalized context sensitivity is a difficult issue. Probably many applications would require the support of generic AI, something that has been evading us despite decades of high-quality research. People are also notoriously sensitive to unreliably working technology; a poorly made context-sensitive inference could lead to serious usability problems.

Self-organized networks, especially in the sensor networking context, have also started to gain more visible research focus. There has been a lot of good academic and industrial research in this field. For example, one can look at the highly interesting *MobileMote* and *SmartDust* initiatives from the University of California at Berkeley and others [9, 10]. Also interesting is the *Terminodes* project in Switzerland that is studying extremely large self-organizing networks with a wide research scope. Naturally, embedded networks will be IP(v6) addressable and interoperable, but these do not necessarily use a full complement of standard TCP/IP. Proximity communication is likely to start with peer-to-peer networking, and small devices will use some consumer electronics, such as a mobile phone or PDA, for gateway functionality (i.e., data migrates hop by hop toward infrastructure).

## HOP BY HOP TOWARD INFRASTRUCTURE

The future heterogeneous networks are complex, and we have to build toward broadband radio networks hop by hop. Literally we have to solve R&D problems one step and challenge at time. Hop by hop also refers here to the requirement to build heterogeneous overlay networks in which we might move messages from narrowband sensor networks toward broadband wireless networks and a fiber optic core network. It is challenging to combine these hugely different networks.

### MULTIHOP COMMUNICATIONS: EXTENDING CAPABILITIES

The current paradigm for wireless communications could be summarized as the *single wireless hop* approach. In the majority of cases wireless systems have only a single wireless link before they are connected with fixed infrastructure, or the end terminal or service. This is notably the case with WLAN technology, where access points serve as bridges to fixed Ethernet infrastructure.

The key characteristics that make the design and development of ad hoc networks unique and challenging include mobility, interoperability between different radio technologies (e.g., IEEE802.11a/b/g/ and Bluetooth) in a heterogeneous topology, the unpredictable wireless channel, and multiple hops. It is still unclear how much wireless multihop networks will develop toward massive MANETs. In general, large-scale self-organizing ad hoc networking requires the support of ad hoc routing protocols, with such development work already handled by the Internet Engineering Task Force (IETF) in its MANET working group. One can argue that regardless of the success level of massive ad hoc scenarios, multihop communications (and the need for ad hoc operations) will be required at least on some scale because of WPANs.

Recently, there has been a lot of interest in building and deploying sensor networks. Trying to network a large number of such low-power mobile nodes is a challenging problem that has been the focus of many researchers. In particular, routing is one of the primary issues to be tackled at the network layer. Existing ad hoc routing protocols are not always practical for use in sensor networks. The main problem with using MANET protocols in a network of mobile sensor devices is that the amount of processing power and memory required are too large, and the protocols are not energy-efficient.

Embedded body-area personal devices and sensors will most probably require at least two hops, usually through a gateway, before they can be connected to services and/or infrastructure. Embedded devices will naturally also perform single-hop peer-to-peer or local client-to-server communications. The great interest in sensor networks has led to a number of forwarding schemes that use the limited resources available in sensor nodes more efficiently. These schemes typically try to find the minimum energy path to optimize the energy usage of a node. There have been a number of clever suggestions to avoid this problem, and work is continuing in the area [11]. Other schemes use stateless forwarding based on some metric or publish-subscribe techniques. In addition, wireless sensor networks require protocols that are data-centric, and capable of data aggregation and effective dissipation of their limited energy.

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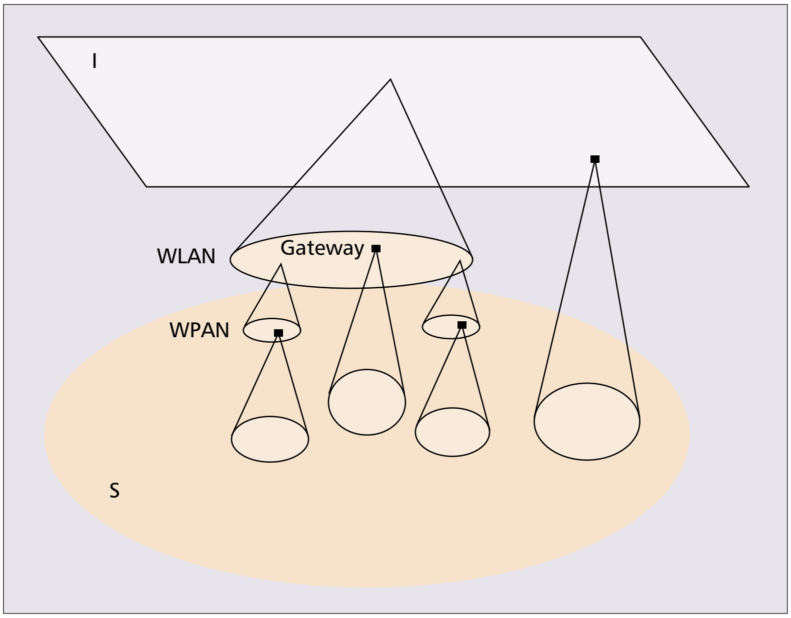


**Figure 1.** *The logical architectural relationship between the Internet and sensor domains. Gateways are the key to interconnecting these two. Mobility increases moving from the Internet domain down to the sensor domain.*

One should also be careful to notice that multihop communications is not always the most energy-efficient method, as pointed out in the recent interesting treatment in [12]. Several alternatives to routing have been proposed in the literature to cater for these requirements. SPIN [13], LEACH [14], and Directed Diffusion [15] are three of those we have found particularly interesting in our own research. SPIN was designed to extend and improve classic flooding by negotiation and recourse adaptation. LEACH is a cluster-based energy-efficient protocol, where the cluster head aggregates information from sensors in its own cluster and passes it to a sink. The Direct Diffusion approach is data-centric and application-aware.

## Sensors and Toward Unified Architecture Picture

The Internet is made up almost entirely of fixed nodes, the locations and addresses of which are known at all times of *connectivity*. The Internet is in a sense *locally bounded*; we know its size, number of nodes, and approximate amounts of traffic loading. Let us call the set of all nodes connected to the Internet the *Internet domain*. Even globally, although we cannot know all the details, there is clear infrastructure available in the Internet domain, because of DNS, global routing, and the fact that different autonomous domains and local networks enforce some structure over chaos.

Wireless nodes and sensor devices have very different requirements than do fixed Internet nodes. The low-power low-definition radio, limited resources, and peer-to-peer pervasive nature of sensor devices limit the need for them to participate directly in the Internet domain. Whereas the size of the Internet is currently limited by human activity, as we are needed to use and maintain the nodes, sensors and embedded devices do not have the same limitation. The potential number of these nodes is boundless. Let us call this domain of all sensors and embedded devices the *sensor domain*. The potential for these devices to be pervasive in every facet of life makes this domain boundless; we are using the term here without a mathematically strict meaning. In general, we do not have a fully connected network, or global addressability or routing in the sensor domain. These domains are envisioned in Fig. 1.

In addition to fixed Internet nodes, different levels of mobile wireless devices make up a hierarchy. WLANs provide high-throughput Internet access and have the capability to cover large areas such as buildings or even entire cities. WPANs are made up of very mobile devices where the network moves with the user, with low data rates and device capabilities. Finally, sensor and embedded nodes make up the final hierarchy of devices, with extremely unpredictable mobility and strict limitations; these devices are not part of the Internet domain, but rather are pervasive in the environment. Of course, even sensor and embedded networks will share some broad characteristics with the Internet domain. For example, we expect them to typically form networks exhibiting some small-world behavior.

With two very separate domains of devices, those associated with the Internet and those pervasive in our environment, the main question is how these two worlds interact in a scalable, functional way. We like many others before have suggested the use of gateways to bridge this gap. A gateway in this sense is simply a device that provides connectivity between the Internet and sensor domains. As devices of the sensor domain will use special-purpose protocols, there is a need to translate to and from IP. This connectivity can be provided through packet translation, socket proxying, or application proxying. In addition to providing connectivity, gateways can provide important security and discovery services for sensor nodes.

Mobility at different domains is shown in Fig. 2. The management of mobility at different levels of this architecture requires very different solutions. The infrastructure of WLANs is quite fixed; often the single wireless hop solution is appropriate, and mobility can be handled in these networks using Mobile IP or in addition Hierarchical Mobile IP. These protocols provide the tracking and management of addresses for nodes. It is WPANs that offer real challenges with the high level of mobility associated with networks traveling with humans. Ad hoc routing protocols can provide the means to interconnect WPAN nodes; however, improvements are needed for ad hoc networks to smoothly interact with WLANs connected to the Internet (e.g., WLAN access points that have the ability to participate in ad hoc routing). Nodes in the sensor domain have such a level of mobility and unpredictability that approaches to mobility management used in the Internet domain cannot even be considered. In this architectural view networking in the sensor domain is based on proximity. Peer-to-peer networks are formed, and limited forwarding can be used to slightly extend the range of radio technology. Gateways to the Internet domain are also limited to proximity interaction with the sensor domain.

### Composable Multihop Networks

Traditional IP-based routing mechanisms are not practical for all multihop networks. Ad hoc routing protocols are very good for supporting mobility and rapid topology changes when cleverly tied with MobileIP support. In sensor networks alternatives must be considered. The simplest solution would be to limit communications between sensors, and between sensors and gateways, to a single hop. While this method of dealing with the routing problems of sensors is limited, it is very attractive in situations with very limited resource requirements. For packet forwarding a number of interesting solutions exist. In addition to the techniques described previously, a more generic approach is the Internet Indirection Infrastructure [16], or i3 for short, which operates in a publish-subscribe-motivated fashion. All data sent is associated with (possibly a stack of) identifiers. Nodes wanting to receive data with given identifiers send a corresponding trigger message to the network, and the forwarding paths are set up accordingly. The i3 approach was originally conceived for internetworking, but because of its level of generality it is also easily adaptable to the sensor networking context. Especially when coupled with i3, traditional middleware technologies can also be used for packet forwarding purposes. Modifications of various service discovery mechanisms such as the Service Location Protocol (SLP) can be used to set up forwarding paths in an on-demand manner.

Gateways serve to enable communications between the lower and upper (WPAN/WLAN/Internet) planes. The main tool used to achieve this is multilayer protocol translation, making the term *gateway* slightly misleading. More complex operation is required because of the expected architectural differences between the networking technologies used in the sensor plane and those used in other planes. For most applications proxying (based on, e.g., HTTP URLs) is an attractive solution. This would mean that the gateway would make, say, the resources of the sensor plane available as services it itself would seem to provide, either by manual configuration or, more attractively, via a service discovery mechanism. Another possibility would be to resort to a transport layer mapping of port numbers, or whatever the corresponding service access points are called. This would require that a transport layer protocol offering the multiplexing of services be used in the sensor plane, and the gateway would perform a mapping between its TCP- or UDP-based port numbering and the multiplexing scheme used in the sensor plane.

## Composable Multihop Broadband WLANs and WPANs

To enable automatic composability inside WPNs, an efficient autoconfiguration mechanism is necessary. The basic configuration of nodes can be accomplished using stateless IPv6 autoconfiguration mechanisms. To incorporate legacy devices running IPv4, a transitional mechanism can be used. For the setting of more elaborate configuration parameters a number of solutions exist. The standard way would be to use some stateful autoconfiguration protocol, such as DHCPv6. A more novel approach, not relying on some devices to function as autoconfiguration servers, would be to use a suitable service discovery protocol to perform *configuration brokering*.

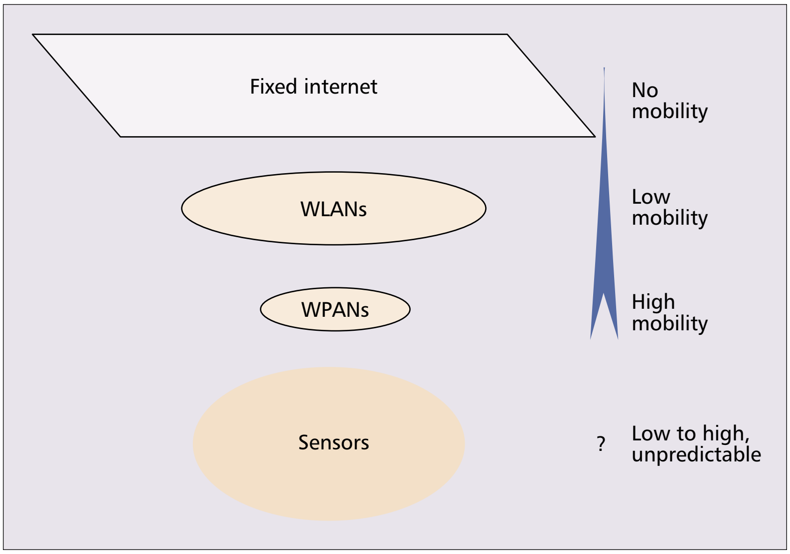


**Figure 2.** *Mobility in the Internet and sensor domains.*

Nowadays, the topics of very extensive research in the area of multihop wireless communications are heading toward good TCP performance within an ad hoc multihop network. Multihop wireless communications is required with composable WLAN/WPAN/sensor networks since it is a key enabling technology to provide rapid and flexible communication between otherwise disconnected wireless islands. One project of many studying multihop wireless communications in the TCP context with both WLANs and other wireless technologies is the European Union 6HOP project, in which we have also been participating. This project is doing both simulations and actual wireless testbed measurements to better understand practical problems related to multihop heterogeneous networks.

One of the major problems in the WPAN/WLAN environment is TCP over (*multiple*) wireless links. This problem itself is a consequence of not only one cause. First, as the topology in the network changes, the path is interrupted, and TCP goes into repeated, exponentially increasing timeouts with a severe performance impact. Efficient retransmission strategies have been proposed to overcome such problems [17]. The second problem has to do with the fact that TCP performance in an ad hoc multihop environment depends critically on different parameters, such as TCP window size. If the window grows too large, there are too many packets (and ACKs) on the path, all competing for the same medium. The third problem is due to the interaction of the 802.11 MAC layer protocol; more precisely, the hidden terminal problem and binary backoff scheme, with the TCP window mechanism and timeout. The TCP/802.11 interaction causes unfairness between competing TCP and in extreme cases capture of the channel by a few flows.

The metric most commonly used by existing MANET ad hoc routing protocols is minimum hop-count. This binary approach implicitly assumes that links are either able to deliver packets (work well) or not (do not work at all). This two-state method does not seem to work well because many wireless links have intermediate loss ratios. Minimizing the hop count usually maximizes the distance traveled by each hop, which most probably leads to low signal strength and higher path loss. An improvement can be made if the route is chosen considering, for example, information about the link quality. This simple idea can even possibly be implemented as a protocol booster, providing a more intelligent link-layer-sensitive mechanism for ad hoc routing protocols without any large modifications.

An expected transmission count (ETX) metric has been proposed in [18]. ETX minimizes the expected total number of packet transmissions (including retransmissions) required to successfully deliver a packet to the ultimate destination. The primary goal of the ETX design is to find paths with high throughput, despite losses.

Finally, one should understand that in most part the perceived problems with multihop (broadband) WLAN technology are related to complex interplay with the current medium access control (MAC) protocol, TCP, and physical layer. Understanding all the issues requires careful analysis and *measurements*. We have found that simulations alone may lead to oversimplification. Due to commercial acceptance, we have to optimize the use of current technology, but definitely there are good reasons to study and suggest alternative solutions, especially related to the MAC layer. Another issue is that especially in the case of multihop communications over present-day systems, one has to pay a

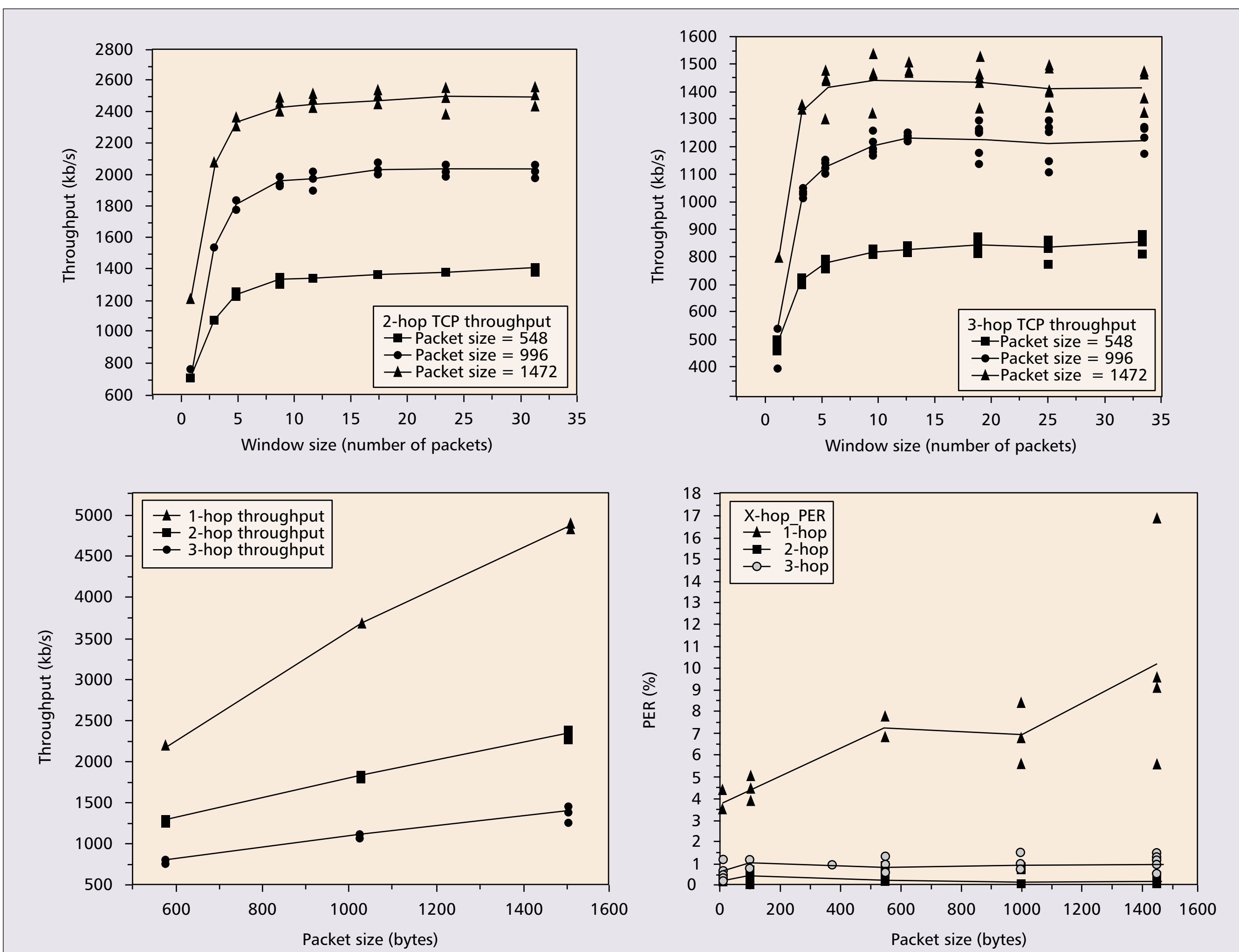


**Figure 3.** *The performance of TCP decreases as the number of hops increases from two (upper left panel) to three (upper right panel). The throughput is shown as the function of TCP window size, measurements shown are done in good signal-to-noise ratio conditions, but the reader should note the large variance in measurements. The lower left panel shows overall behavior (note that theoretical throughput for TCP over one hop could be 6.1 Mb/s without RTS/CTS, and over 5 Mb/s with RTS/CTS enabled). The bottom right panel shows how the probability for packet errors can increase rapidly with multiple hops in realistic environments; in this typical measurement we see that the third hop is very error-prone, and the difference between packet error rates of different hops is quite high, and can be caused by most trivial changes in the environment (e.g., rotation of a WLAN node).*

*performance price*: in order to get multihop connectivity, we might lose in other areas (e.g., lower bit rate, higher interference, and higher power consumption); as with everything else there is no free lunch. Because of this there is a need for advanced multihop architectures [19]. If one is using a forwarding node that has only one wireless interface (e.g., a single IEEE802.11 card) the performance in bit rate is always about half, even in perfect conditions. The use of multiple wireless interfaces with interference mitigating technologies makes sense, and this might lead to building specialized forwarding nodes and gateways for professional use. Moreover, the systems, which have multiple interfaces with different technologies, have to be carefully designed with buffering, gateway, and interference minimization functionalities. In order to give some quantitative examples, we show in Figs. 3 and 4 some representative measurements done in the 6HOP project. Figure 3 shows how the achieved throughput decreases with increasing number of hops (only a single wireless IEEE802.11b interface within each node). In Fig. 4 we show how the throughout of AODV can be highly variable over three-hop error-prone WLAN links.

In summary, it seems plausible that in the civilian consumer market, the number of wireless hops should in the near future be limited to maximize the use of resources. We envision a situation where the typical hop count would be most probably two and maximally three. Thus, one can guarantee reasonable broadband capability. Moreover, as for the integration of WLANs and 3G (cellular), it is quite possible that mobile phones and PDAs will work as gateways for small-scale devices and sensors, providing a hop toward broadband infrastructure.

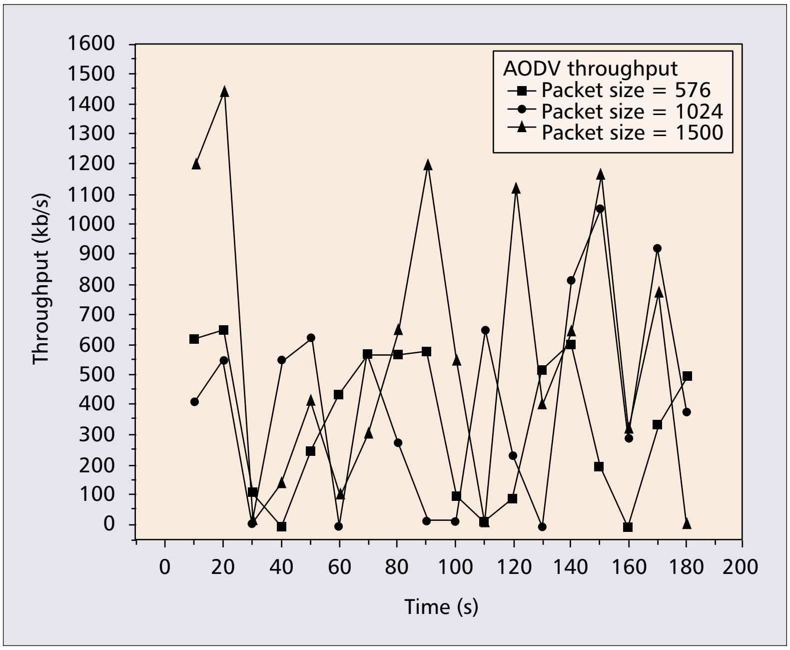


**Figure 4.** *The performance of AODV with TCP over an error-prone three-hop IEEE802.11 link.*

## Full Speed to Alice in Wonderland

The one emerging problem is the increasing complexity of systems. In terms of the hourglass model, it is very important to try to keep the waist of IP as narrow as possible. It is also imperative that we should constantly rethink the end-to-end principle; it might be dangerous to discard it for short-term gains. As trillion-device networking is becoming a reality, we should regularly reconsider our basic assumptions on (wireless) packet networking. There is certainly room for more trailblazing research that might lead to what is finally called IPv7, or most probably something else. A long-term network research goal should be to challenge existing paradigms and systems, including the Internet, and boldly look for new possibilities. In any case, we should try to keep overall complexity as low as possible.

The megatrends are toward more software, higher bit rate, ubiquitous access, and extreme scalability (number of nodes up to a trillion, bit rates from 1 b/s up to 100 Tb/s). This leads us to the point where R. Steele was asking "what we are doing if the goal of communications at any time from anywhere at any speed has been achieved?" Unfortunately we do not have the answer, but we agree that we should ask this question and use our partial answers as guidance.

In this last part of the article we take a glimpse into Wonderland. With the proliferation of ubiquitous wireless and multihop Internet applications, we are apparently entering an era when we must consider even possible social and ethical questions.

Miniaturized cameras and other sensors with wireless communications capabilities are (already) becoming ubiquitous. This will lead to a jungle of complex issues on privacy, authentication, and use of information. When one expands this vision to the completely ubiquitous world that includes embedded network connectivity into virtually every electronic gadget with the capability to store and compute large databases in grids, one can see that we have a potentially dangerous situation on our hands. But there are also wonderful opportunities. We should prepare to regulate the situation with technological, legal, and social means.

The reader should note that a big brother society is not the only danger. There are also potential problems with voyeurism, "dumpster diving," exploding media misuse, freedom of speech, responsibility of communications, and a plethora of other problems. Emerging biotechnology combined with wireless communications and embedded Internet gateways can also lead to difficult questions. They start with the obvious liability and security issues. Potentially we end up with issues such as whether someone can subpoena access to a cochlear implant with wireless access in order to use it as a wiretap? If we truly have memory implants, are these technically recorded memories protected by law; that is, if you have something like Vannevar Bush's Memex implanted in your brain is it legally a part of yourself, and hence protected against intrusion or even subpoenas? Networked bioelectronics combined with global networks might blow the number of networking capable devices beyond $10^{15}$ nodes. Security, privacy, and robust-

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ness will gain even more importance. One could also expect that new issues such as wireless environmentalism can become issues in the future. It is interesting to note that the number of computing elements and connections start to become comparable to those we find in biological systems (including brain) and statistical physics.

The opportunities of multihop broadband wireless communications networking combined with pervasive computing devices are almost limitless; when this is combined with the future visions of nanotechnology-based nanoRadios surrounding us like clouds, we are entering the domain of science fiction and some hard questions on what we are going to do with that capability. In the not so far future, suddenly interdisciplinary and even somewhat philosophical research might become a must.

## CONCLUSIONS

Wireless networks and internetworking applications will overall become a part of our society, and some aspects of wireless technology will be present almost everywhere. This will lead to great challenges and the need to reevaluate many technical assumptions and designs we are using today. The social effects of technology will become more important. Although the roadmap toward the near future seems reasonably clear, one should not underestimate the integration challenges — and inevitable surprises and technological breakthroughs. When we vision further toward *real* ubiquitous computing and intelligent software agents with broadband wireless ubicommunications and terabit-per-second optical networking, the research challenges will be demanding. The challenges in networking and wireless communications have not ended, and the field is not in decline, although some observers have been claiming so. On the contrary, the long-term future seems interesting. The main challenge will be the complexity of our technology and science overall.


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