Abstract

A "fourth generation" of wireless systems, likely to appear after the successful deployment of the current third-generation systems, is frequently debated these days. This article presents some of the results of the Fourth Generation Wireless project (4GW) of the Personal Computing and Communications program (PCC), the major Swedish academic research effort on future communications systems, launched in late 1997. In the 4GW project, scenarios have been used as tools for formulating relevant research topics related to future wireless systems. By working with scenarios the project group has been able to challenge some of the assumptions commonly made in the field of wireless research. Since the project group is multidisciplinary, the work has also helped the members of the project group to understand the differences between the research traditions to which they belong. The scenarios, as well as the ensuing research into various wireless related topics, point to a vision of fourth-generation systems where "low-hierarchy" user-deployed infrastructures are the prime candidate. Fourth-generation systems will offer short- to moderate-range communications with very high data rates (>100 Mb/s). They are likely to employ array signal processing and ad hoc operation to provide the required coverage. A key aspect of their design will be the fact that they will be deployed in environments where large-scale wireless, and wired, infrastructures are already in operation.

4th-Generation Wireless Infrastructures: Scenarios and Research Challenges

AURELIAN BRIA, FREDRIK GESSLER, OLAV QUESETH, RICKARD STRIDH, MATTHIAS UNBEHAUN, JIANG WU, AND JENS ZANDER
ROYAL INSTITUTE OF TECHNOLOGY, KTH
MAXIME FLAMENT, CHALMERS UNIVERSITY OF TECHNOLOGY

A "hot" item, frequently debated in the wireless community these days, is whether there is such a thing as a "fourth generation" (4G) of wireless systems that is likely to appear after the successful deployment of the current third-generation (3G) systems, say five to ten years from now. This new generation of wireless systems is supposed to complement and replace 3G systems, as well as second-generation (2G) systems that have already been in use for about a decade. A "classic" approach would design such a "system" in the same way as previous generations of wireless systems, that is, yet again focus on higher data rates (now beyond 2 Mb/s) and find new frequency bands for a worldwide standard (e.g., [1]). For a number of reasons, however, it is not obvious that the roadmap is this straightforward. One of the main concerns is that 4G wireless infrastructures will be deployed in an environment where many other types of wireless, and wired, communications systems are already present. Furthermore, some people argue that future wireless communications will become focused on services and user needs, thereby forcing the mixture of available wireless infrastructure elements to be used in a more transparent way [2, 3]. In that case, the previously so important air interface standard and frequency band issues will become secondary concerns.

By definition it is difficult to make precise statements on the nature of this kind of vision. An important factor contributing to this uncertainty is that we have very limited knowledge about the future environment in which a 4G wireless infrastructure should function. Which of today's systems *will still* exist when a potential 4G infrastructure is deployed? Which systems and solutions will be considered successful then? What technical bottlenecks will be apparent 10 years from now? What market impact will 3G wireless systems have? How will this affect user behavior and user demand? How much money are prospective users willing to pay for services provided over this infrastructure?

As these questions indicate, defining relevant research topics with regard to future systems is not an easy task. Nevertheless, experience tells us that fundamental research related to 4G systems has to be carried out today in order to make it possible to deploy them a decade from now. We can thus formulate the key issue treated in this article:

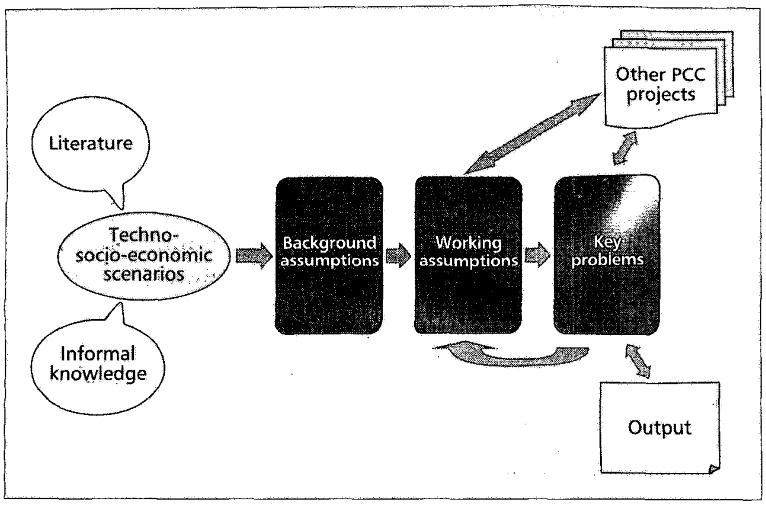
> How can reasonably relevant research questions related to future wireless infrastructures be identified?

This article presents some of the results of the Fourth Generation Wireless project (4GW) of the Personal Computing and Communications program (PCC), the major Swedish academic research effort on future communications systems, launched in late 1997 [4]. In 4GW a scenario-based approach has been used to tackle the issue of identifying suitable research topics. In the article we present this method. We also give an overview of some research results from the project. Finally, we conclude these results in terms of a vision of what 4G wireless infrastructures might become.

Identifying Reasonable Assumptions

Perhaps the most difficult issue in any scientific research endeavor is to identify reasonable assumptions. Most research therefore takes for granted assumptions that are common to the tradition in which it is conducted, that is, follows certain paradigms [5]. In general this is a very effective approach, but when a study aims very far into the future, a more critical appreciation of the assumptions becomes necessary simply because they are likely to change over the time period the

1070-9916/01/$10.00 © 2001 IEEE



■ **Figure 1.** *An overview of the 4GW work process. Scenarios were created using literature and other current knowledge sources. Key research issues, critical for the success or failure of the scenarios, were formulated and researched.*

study spans. However, there is also a more fundamental reason. The assumptions taken for granted in the study are in part based on conditions external to the study. Implicitly, the researcher therefore also assumes these external determinants to remain stable over the course of his study. This is clearly not the case in the 4GW project.

How then does one handle future uncertainty in research projects aiming to provide results useful 10 or more years from now? The approach chosen in the 4GW project has been to work with scenarios. A scenario is a tool to explore a possible, plausible future by identifying key technical and social developments required for it to be realized. The point of a scenario is not to predict the future, but to create an awareness of which future developments are possible. It is thereby possible to both prepare for what the future will hold and identify the developments needed to influence the direction the future will take.

The research model used in the 4GW project is outlined in Fig. 1. As the figure demonstrates, the process began with the creation of techno-socio-economic scenarios based on literature studies and more informal sources of knowledge. The studied literature consisted of scenario methodology, as well as scenario work done by others (e.g., Ericsson [6] and Siemens [7]). The informal experience-based knowledge was gathered through Delphi interviews with academics and industry professionals. The resulting scenarios have been used as important input for the formulation of some basic assumptions that are an expression of the expectations and visions of the entire PCC program. From the basic assumptions, a number of working assumptions have been drawn. They in turn represent the more operational goals of the research program, and have been used to formulate the actual research problems of the 4GW project. By working in a multistage process, it has been possible to translate "fuzzy" societal developments into consequences for technologically defined research problems.

Three scenarios have been formulated: Pocket Computing, Big Brother, and Anything Goes. They address user behavior and lifestyle, telecommunications market evolution, development of supporting technologies, and evolution of values and society. The scenarios are outputs that portray the essence of what the world might become. The three scenarios are outlined below. More extensive narrative descriptions of the scenarios can found in a full report [8] published by 4GW in 1998.

Anything Goes! — The diversity of telecommunications equipment has increased dramatically, as well as the possibilities of manufacturing cheap coexisting products. Manufacturing companies have become dominant in the telecom world. They advocate open de facto standards, and use software solutions to create flexible multistandard equipment. Because of dramatic price reductions, both residential and business environments have wireless LAN solutions. They are operated by a multitude of operators, and the end users have great freedom of choice in selecting where to purchase wireless services. Competition between operators, as well as equipment providers is fierce, and new wireless products and services appear all the time. Services and equipment are affordable for almost everyone in the industrialized world, which tends to narrow the social gaps in society. Equipment manufacturers, large and small, dominate the telecommunications scene.

Big Brother — As more and more personal information is available in the information infrastructure, personal integrity, and privacy have become major concerns for the ordinary user. There is a widespread call for regulation and government intervention to ensure information integrity and secure networks. All citizens and companies wishing to deal with any aspect of computing and communication need some kind of regulatory approval. In the private sphere, most public information services use broadcasting. The complexity of products and services has increased, and thus also the cost. Service, transport, and equipment providers have been reduced to a few large actors (brands) that, in the public eye, can be trusted. Regulators dominate the telecommunications scene.

Pocket Computing — Technological development continues at a high pace throughout the world, but due to financial and educational differences, society is divided between those who can follow the development and those who cannot. Parts of the population have access to a multitude of advanced services, whereas others use simple services adapted to their needs. Service providers offer a wide range of different services (which may include specialized hardware) tailored to various user groups. Mobile multimedia services mainly focus on high-end consumer and business needs. Global solutions are available, but much too expensive to be affordable for the average user. Cultural and educational differences between nations, and different strata in society, have led to political instability and unrest. A few operators and some very large manufacturers use standards to maintain their strategic position, and dominate the telecommunications scene.

Implications: The Working Assumptions

From the scenarios a set of key developments in the information and communication fields could be identified. They were expressed in terms of the following working assumptions.

Telepresence ... is an application that will be used to create virtual meetings between individuals, and provides full stimulation of all senses required to provide the illusion of actually being somewhere else. With efficient data compression and fast sensory feedback, the bandwidth required for tele-presence is less than 100 Mb/s. The data stream is dominated by high-resolution full-motion video. Multiparty meeting processes is one of the major communication patterns foreseen for this application. Meeting processes will be mainly real-time. This type of application is likely to be the technically most demanding encounter in personal communication systems.

Information anywhere, anytime ... with virtually seamless connection to a wide range of information services is a key feature of the future information infrastructure. Information access of large volumes of data, pictures, video, and so on will be nearly instantaneous in small portable terminals. High data rates will be required for high-volume data transfer applications such as video retrieval. The traffic pattern will be highly asymmetric. Information provisioning will be dominated by educational and recreational material.

Intermachine communication ... will be an important application/service. It will range from simple maintenance routines (e.g., refrigerator telling repair shop it's broken) to sophisticated massive data exchange (e.g., camera and PC/TV exchanging video/picture information). All cars will have a wireless interface as a standard feature, as will household and office equipment costing as little as US$20.

Security ... will be an indispensable feature of the future infrastructure. Data integrity and protection against unauthorized access will be key features for providing reliable services for banking, electronic payment, and handling of personal information. Schemes that reliably prevent unauthorized tracking of users and other intrusions in the private sphere will be in operation.

One-stop shopping ... services will be provided in a "turnkey" fashion directly to the consumer at the point of sales. The store (information provider) will take full responsibility for the service, as well as for any hardware or software provided.

Nonhomogeneous infrastructure ... consisting of several switching fabrics and a multitude of physical media will be the rule. All elements of significance will be digital. The fixed backbone structure will be dominated by connectionless packet switching (IP-style). The new air interfaces in wireless systems will also use packet switching technology. The wireless infrastructure will consist of a multitude of air interfaces inherited from earlier generations of wireless systems. Packet-oriented wireless systems will offer high data rates of up to 100 Mb/s for hand-portable use. An overlaid architecture will provide seamless transparent internetworking using all kinds of air interfaces.

Public and private access mixed ... Public wireless access quality and bandwidth will vary. Higher data rates will be confined to dense urban areas, office environments (private/public systems), and homes (private systems). Operators and service providers will provide partial coverage for non-real-time wideband (10 Mb/s) information access in most public places (info stations). Rural area information access bandwidth will be limited to 1 Mb/s, but will provide reasonable coverage along all main highways and in communities of more than 100 inhabitants.

Ad hoc, unlicensed operation ... will dominate and many different actors will provide parts of the infrastructure. Ad hoc networking (spontaneous deployment, self-planning) in unlicensed bands (the 5 and 60 GHz bands) will play an important role, and compete fiercely with existing public operators, who will experience dwindling market shares. Techniques for efficient multi-operator (private/public) sharing of unlicensed spectrum have been developed. Ad hoc structures, where the equipment of the users (companies or even individuals) provide part of the infrastructure, will be adaptive to possible new communication patterns. Control of the new emerging ad hoc networks (routing, mobility, etc.) will be fully distributed and highly reliable.

Multimode access ports in public systems ... with multiple access air interfaces will be used to accommodate a wide range of terminals. Large operator systems will use advanced access ports with adaptive antennas that self-configure with noncritical installation procedures (self-configuration) to reduce cost. Access ports (wireless gateways) in ad hoc access systems, on the other hand, will be simple single-mode (single air interface) devices. The cost of access port hardware in these systems will be negligible compared to the cost of planning and physical installation.

Terminals ... will exhibit a large range of bandwidths, from less than 10 kb/s (simple appliances) to 100 Mb/s (telepresence terminals). The battery life of personal terminals will be at least one week. Battery capacity/weight/volume ratios will increase by an order of magnitude from those of today. Terminals in the 5 and 60 GHz range will use advanced adaptive antennas. Terminals will either be multimode multifunction terminals or single-purpose cheap terminals designed solely for a specific service or function.

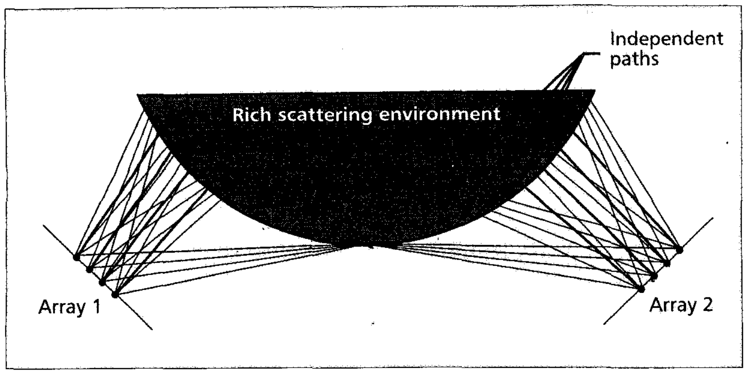
Focal Areas for 4GW Research

Using the process model in Fig. 1, a number of research problems relevant to wireless infrastructures have been derived. A key recurrent problem is to provide high data rates everywhere in a way that is *affordable* to the general public. The first part of this challenge, designing wireless system with high data rates, has attracted considerable interest in the research community. Our view, however, is that the real challenge is to combine this with affordability. As was shown in [9], the cost of providing wireless bandwidth everywhere, with the current "cellular" design paradigm, is essentially proportional to the data rate; that is, the cost per transmitted bit is almost constant, independent of the instantaneous data rate of the system. This is of course a devastating blow to high-bit-rate consumers, using, for example, high-quality sound and video applications.

The 4GW project has conducted a number of feasibility studies focusing on techniques and architectures that, if used to their full potential, could significantly change the cost and performance of wireless systems. The project has participants from various information and communication technology research fields. While the project work is conducted in a cooperative fashion, project members also belong to their own research tradition. Problems, methodology, tools, study objects, and so on vary between these traditions. Below follows an account of the subprojects of 4GW. Each has been formulated to study or challenge one of the working assumptions described in the previous section. Together with his advisors, one Ph. D. student has performed the research associated with each subproject.

Broadband OFDM Air Interface Design

The working assumptions state that user-deployed access points and self-planning capabilities will be key factors in making the 4GW infrastructure economically viable. Short-range broadband wireless systems play an important role in this context. In several countries, the 60 GHz unlicensed band has been proposed for this purpose, offering at least 5 GHz of available bandwidth. In a 60 GHz system, our research shows that coverage is not the main limitation in indoor office deployments, but rather that unstable handover situations are caused by the fact that interference occurs in short bursts. Using a ray tracing simulated channel, we have



■ **Figure 2.** *Principal characteristics of dual antenna arrays in rich scattering environments. The rich scattering environment provides independent paths between the arrays.*

studied the dynamics of the 60 GHz time-varying channel in particular situations typical for office environments. The studies have also been extended to shopping mall environments. The results give an insight into the time variations of the signal-to-interference ratio. However, the simulations were based on a single-frequency network and omnidirectional antennas. Indirectly, we have showed that diversity at the terminal side is a prerequisite for functioning systems. Using directional antennas and dynamic resource allocation will decrease the interference issues, but the problems due to the short timescale variation of the interference will always remain more difficult to handle than in lower frequency bands.

The impact of human body shadowing on the 60 GHz channel has also been studied. This is a particularly important problem when considering imperfect installation of the infrastructure. The strong attenuation of the human body at 60 GHz considerably decreases the received power and changes the character of the multipath fading statistics, so the resulting error floor increases with the shadowing density. This can be described with a modified Saleh and Valenzuela indoor channel model [10, 11]. Exploiting site diversity can considerably improve system performance, since it effectively reduces the shadowing probability. Despite the difficult propagation situation at 60 GHz, it appears feasible to design wireless systems for high data rates that function in office areas or public hot spots of high-density population.

Smart Antennas

In order to provide high date rates at a low cost, smart antenna systems have been proposed for short-range WLAN-type systems. Using the 60 GHz band requires an increased number of access points, but may allow inexpensive radio access equipment. Systems at 5 GHz offer greater range, and have the advantage that several users can share one access point, which offers flexibility for the operator at the cost of more complex access points. Our research results so far show that dual arrays at above 5 GHz, in indoor environments, fulfill the 4GW requirements of link capacity. Furthermore, we have found that it is feasible to deploy an antenna array on the user terminal, since one wavelength (~ 50 mm) is sufficient element separation to utilize the rich scattering characteristics of the channel (Fig. 2). The results have been derived from analyses and capacity computations on measured multiple-input-multiple-output channel data [12].

The results indicate that operation at 5 GHz is an important alternative in 4G wireless systems. In addition to further work in this area (e.g., to map the network properties), an infrastructure study is needed in order to compare coverage and QoS vs. infrastructure cost for the proposed systems.

Wireless Infrastructure Architecture

The assumption in the program is that high-data-rate wireless services can only be provided at a low cost if infrastructure deployment costs are reduced by some orders of magnitude. In current cellular systems, large sums are spent for antenna site acquisition, network planning, and installation of base station transceivers, while hardware components are continuously getting cheaper. If wireless networks could be deployed according to the wireless LAN paradigm (i.e., by customers themselves wherever wireless access is desired) and still offer sufficiently high data rates and guarantee adequate coverage, large cost savings would be possible. The high data rates intended for 4G infrastructures will require the use of unlicensed spectrum with sufficient bandwidth to accommodate such high capacities. Acceptable bandwidth can be, found for example, around 17 and 60 GHz [13]. Propagation at these frequencies suffers high free-space loss, strong shadowing by humans, and high attenuation by common building materials. The number of wireless access points (APs) required to achieve sufficient coverage is therefore high.

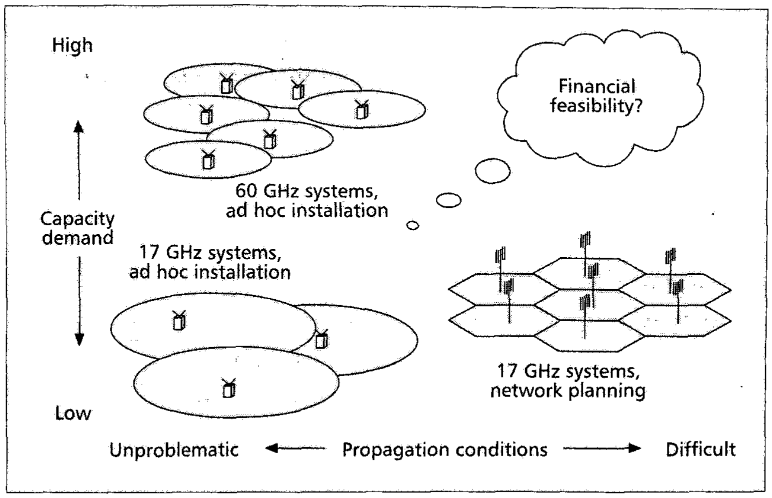
REFA's air interface, a 128-carrier orthogonal frequency-division multiplexed (OFDM) air interface with 130 Mb/s link layer throughput and a 50 MHz channel bandwidth, was adopted for the purpose of making comparisons. Three characteristic environments — an office setting, a shopping mall, and a campus area — were used to evaluate system performance.

Our results show that user deployment is indeed a viable alternative to traditional infrastructure installation methods. In particular, dense networks, typically needed to satisfy the high-capacity demands in, say, office environments, are tolerant of arbitrary placement of the APs, as long as they are reasonably uniformly distributed over the entire area. In densely populated large buildings such as shopping malls, train stations, or airports, user deployment also achieves acceptable performance, although AP placement will require some coarse preplanning. Our results (Fig. 3) indicate that 17 GHz systems should be recommended for such scenarios since 60 GHz systems achieve very limited cell radii, hence requiring an extremely high number of APs to achieve adequate coverage. Outdoor scenarios are normally not suited to the user deployment approach. Even for 17 GHz systems, rather sophisticated network planning is necessary to attain sufficient coverage.

Wireless Resource Management in Multiple-Operator Infrastructures

Future wireless infrastructure and services will be offered by many different types of operators and service providers. Various systems will have to coexist in an ad hoc fashion, often in unlicensed environments. There are two obvious solutions to this problem. Either there will be a single operator in each frequency band, over whose infrastructure a multitude of services will be provided by different actors, or there will be several access infrastructures that must be able to coexist in the same frequency band.

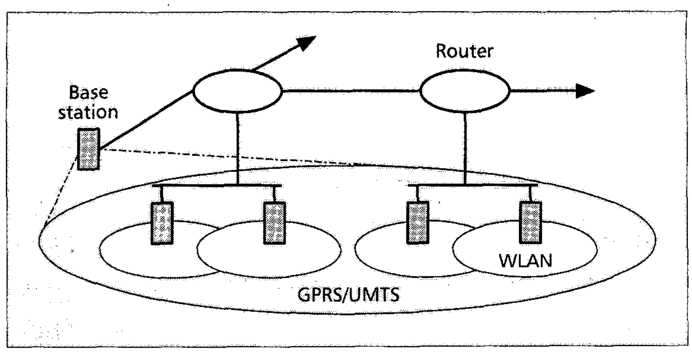
The number of operators and service providers will increase, as will the capacity requirements of the services they offer. In order to make future wireless services reasonably priced, we need to find more efficient methods to share frequency spectrum. Traditional licensing techniques, widely used today, provide rigid solutions with poor performance. The aim of this subproject is to determine the feasibility of unlicensed operation for spectrum sharing. It has already been established that coexistence in some sense is possible in unlicensed bands. However, an analysis of the total efficiency of different infrastructure deployments has not been made. Research results indicate that efficient infrastructure deployment is possible in environments where multiple operators share unlicensed frequency spectrum. Unlicensed infrastructure deployment can be as efficient as traditional deployment, based on licensed operation. The technical feasibility of such evolutions has thus been justified. Different techniques for frequency sharing have been studied in relation to infrastructure deployment, and frequency hopping appears to be the preferred alternative. Isolation (i.e., attenuation) between operators' infrastructures improves the total available capacity. Techniques for increasing isolation will thus become key in an unlicensed environment. Examples of such techniques include smart antennas.



■ **Figure 3.** *Capacity demands and propagation conditions for 17 and 60 GHz systems. Depending on differences in capacity requirements, as well as the propagation environment in which an installation is to be made, different types of system implementations are feasible.*

Seamless IP Mobility Support for Mobile Applications

Future telecom infrastructures will consist of a set of heterogeneous networks using IP (or similar) as a common protocol (Fig. 4). In most cases, both wired and wireless networks will be used for a single communication session. Since the network infrastructure is not deployed in a orderly fashion, protocols need to be flexible and robust. IP mobility support (Fig. 5) will be an indispensable feature of future mobile communications services. Although both mobile communications and the Internet have been extremely successful during the last decade, the seamless integration of these two is still a great challenge in both areas. We have therefore investigated how seamless IP layer mobility can be supported in 4G wireless infrastructures and propose enhancements to both Mobile IP and IP multicasting protocols.



■ **Figure 4.** *The 4GW infrastructure will be built with heterogeneous wireless networks. IP will be used above different link layer wireless networks such as wireless LAN and GPRS/UMTS.*

Using our proposal, IP layer handover latency for IP multicasting is small enough to support real-time applications. In the case of Mobile IP, we believe it will be possible to achieve seamless handover in a near future. The research results demonstrate the feasibility of a heterogeneous network infrastructure, evolving through an integration of the current Internet and wireless networks.

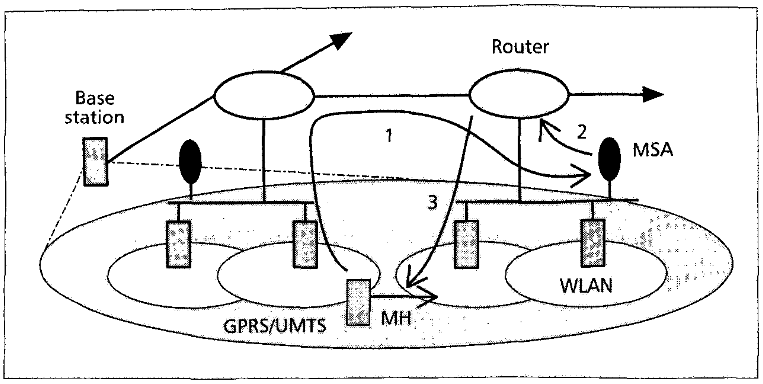
Other Research Challenges

Besides the areas described above, where explicit research efforts have been made, several other important research areas have been identified, and in some areas work has begun.

Asymmetric Wireless Infrastructures — High demand for mobile Internet and interactive services will characterize the use of future wireless systems. As a consequence, a large amount of traffic will be asymmetric, with user terminals requesting large amounts of data. Exploiting this fact in network design may have significant implications on infrastructure deployment costs since higher transmitter powers can be used in base stations. Emerging examples include the integration of digital broadcasting systems with personal communications systems. Technical problems with these types of systems involve resource allocation and deployment strategies as networks become denser and migrate to microcellular configurations. Probing the technical feasibility and scalability of such systems is an interesting challenge.

One-Stop Shopping — *Terminal and service adaptability* — Since the future user will want his services available on the spot, he/she is not willing to manually configure his/her hardware devices and network services. This has to be done by the devices themselves. Automatic adaptation to various standards and infrastructures that provide different bandwidths at different delays opens up a wide area of research. There are questions on how to most efficiently adapt to new conditions (networks, bandwidth, etc.), when to switch between systems, and how to determine which layer should be responsible for different functions [14]. Security issues in these environments represent major challenges.

Infrastructure Deployment Strategies — *The business models* — The high bandwidths projected in our scenarios will require a dense and potentially costly infrastructure. Who are the actors on the infrastructure market? Will the market volume in 2010 be sufficient to support an infrastructure that fulfils the requirements of the PCC vision? Will there be an evolutionary path along which the involved players can make money? (See [15].)



■ **Figure 5.** *In our proposal, a mobility support agent (MSA) architecture is used to support seamless IP layer handover. A mobile host intelligently registers to the MSA in the next visiting network before its handover (1); this network acts as a proxy so that the mobile host can set up in advance the necessary communication states (2). When the mobile host performs handover, it will suffer limited traffic loss (3).*

Conclusions

The systematic process to find key research issues for 4G wireless infrastructures, based on the PCC vision of affordably providing high data rates everywhere over a wireless interface, has been presented. Using a scenario-based approach, the work resulted in three major scenarios describing possible "telecom futures." Key technical and business-related research issues were derived, and working assumptions for the project were formulated based on the scenarios. An overshadowing barrier in current system design, prohibiting the implementation of the vision by current techniques, has been identified: the cost per transmitted bit remains almost constant as we increase the data rate. A number of feasibility studies have been conducted in the project, studying key techniques or technologies that promise to break these cost/performance barriers.

The results of these ongoing studies show that a user-deployed infrastructure remains a viable candidate for short-to-moderate range wireless systems with very high data rates (> 100 Mb/s). Further advances in array signal processing are shown to be practically applicable in these environments, with the potential of substantially reducing the number of required APs. Ad hoc multiuser/multi-operator systems can be made to work in these environments, but without careful system design this will incur a severe performance penalty. Conventional code-division multiple access (CDMA)-type solutions are not useful in this context. Mobility management remains a great challenge in the "low-hierarchy" network architectures outlined in the working assumptions. However, for the most demanding applications (multicasting/multiparty teleconferencing) significant progress has been reported.

In addition, the scenario activities provided great benefits to the project. They were a highly efficient way to start a thought process among the project participants, thus creating much better awareness of the environment in which our research project is set. Strong interfaces have developed between subprojects, allowing a technical information flow and defining research responsibilities, thus tying the members of the 4GW group together. The scenario work has also provided confidence that the group is working on the right problems. In fact, the scenarios have gained acceptance and generated discussions throughout the entire PCC program, where they serve as a common platform for discussion of future systems and architectures.

References

[1] M. Hata, "Fourth Generation Mobile Communication Systems Beyond IMT-2000 Communications," *Proc 5th Asia-Pacific Conf. Commun. 4th Optoelect. Commun. Conf.*, vol. 1, 1999, pp. 765–67.
[2] J. Pereira, "Fourth Generation: Now, Its Personal!," *Proc. PIMRC 2000*, vol. 2, 2000, pp. 1009–16.
[3] M. Flament *et al.*, "An Approach to 4th Generation Wireless Infrastructures — Scenarios and Key Issues," *VTC '99*, Houston, TX, May 1999.
[4] B. -A. Molin, "Personal Computing and Communication — A Swedish Strategic Research Program," *Proc PIMRC '98*, Boston, MA, Sept. 1998.
[5] T. Kuhn, *The Structure of Scientific Revolutions*, Univ. Chicago Press, 1962.
[6] Ericsson, Scenarios, 18 Dec 2000, http://www.ericsson.com/SE/kon_con/tema_indepth/indepth/id1_97/index.html, (also published in Kontakten no. 1, 1997.
[7] Siemens, Scenarios, 18 Dec 2000, http://www.ic.siemens.com/CDA/ Site/GHTML/box/1,1562,5408-1-0,00.html
[8] M. Flament *et al.*, "Telecom Scenarios 2010 — A Wireless Infrastructure Perspective," http://www.s3.kth.se/radio/4GW/public/Papers/ScenarioReport.pdf
[9] J. Zander, "On the Cost Structure of Future Wideband Wireless Access," *Proc VTC '96*, Atlanta, GA, May 1996.
[10] A. A. M. Saleh and R. A. Valenzuela, "A Statistical Model for In-door Multipathpropagation," *IEEE JSAC*, vol. SAC-5, Feb. 1987, pp. 128–37.
[12] R. Stridh, P. Karlsson, and B. Ottersten, "MIMO Channel Capacity on a Measured Indoor Radio Channel at 5.8 GHz," *34th Asilomar Conf. Signals, Sys. and Comp.*, Pacific Grove, CA, Oct. 2000.
[13] "Relating to the Use of Short Range Devices (SRD)," CEPT/ERC Rec. (Tromsø 1997), CEPT/ERC/REC 70-03 E, Dist. B.
[14] Special Issue, Adapting to Network and Client Variability, *IEEE Pers. Commun.*, vol. 5, no. 4, 1998.
[15] Nat'l. Res. Council, Comp. Sci. and Telecommun., "The Unpredictable Certainty — Information Infrastructure through 2000, Washington, DC: Nati'l. Acad. Press, 1996

Additional Reading

[1] P. Schwartz, *The Art of the Long View*, Doubleday, 1991.
[2] F. Lagergren *et al.*, "Scenarios — A Tool for Starting a Research Process," *PCC Wksp. '98*, Stockholm, Sweden, Nov. 1998.
[3] M. Flament, "On 60 GHz Wireless Communication Systems, Licentiate Thesis, Technical report No. 365L, Chalmers Univ. of Tech., Gothenburg, Sweden, Dec. 2000.
[4] Q.H. Spencer *et al.*, "Modeling the Statistical Time and Angle of Arrival Characteristics of an Indoor Multipath Channel," *IEEE JSAC*, vol. 18, issue 3, Mar. 2000, pp. 347–60.
[5] M. Flament, M. Unbehaun, "Impact of Shadow Fading in a mm-wave Band Wireless Network," *Proc. Int'l. Symp. Wireless Pers. Multi. Commun.*, Bangkok, Thailand, Nov. 2000.
[6] J. Wu and G.Q. Maguire Jr., "Agent Based Seamless IP Multicast Receiver Handover," *Proc. PWC 2000*, Sept. 2000.

Biographies

AURELIAN BRIA [S'00] (aurelian@radio.kth.se) is a Ph.D. student at the Department of Signals, Sensors and Systems of the Royal Institute of Technology (KTH). He received his M.S. degree in electrical engineering from the Politechnical University of Bucharest in 1998. In autumn 2000 he joined the Swedish PCC program, thus starting research in the field of asymmetric wireless infrastructures.

FREDRIK GESSLER [S'96] (gessler@kth.se) is currently pursuing a Ph.D. at the Department of Industrial Economics and Management at the Royal Institute of Technology (KTH), Sweden. He received his M.S. degree in industrial engineering and management from KTH in 1995, and completed his Licentiate of Engineering degree in 2000. His research focuses business aspects of wireless infrastructures, especially in relation to the development of technical standards for wireless communications.

OLAV QUESETH (olav.queseth@radio.kth.se) is currently pursuing his Ph.D. at KTH, Stocholm, Sweden. He earned his M.Sc. in computer engineering from Chalmers University of Technology in 1994, and has previously worked with telecom management systems. His research focuses unlicensed operation and methods to ensure peaceful cooperation.

RICKARD STRIDH (rickard.stridh@s3.kth.se) is currently pursuing his Ph.D. in signal processing for wireless communication. He received his M.S. degree in electrical engineering from Lund University, Sweden, in 1995, and his Engineering Licentiate degree in signal processing from the Royal Institute of Technology, Sweden, in 2001. In 1996–1997 he was with the Swedish Air Force Material Command as a radar systems engineer. His research interests include smart antennas for wireless communications and their impact on system architecture. Main foci are radio resource management for array antenna systems and the use of MIMO channels.

MATTHIAS UNBEHAUN (matthias@radio.kth.se) received his M.S. degree in electrical engineering from the University of Erlangen-Nürnberg, Germany, in 1994. He then joined Corporate Research and Development at Robert Bosch GmbH, Hildesheim, Germany, where he worked on the design and implementation of digital audio broadcasting (DAB) receivers, also serving as chair for European standardization groups. Since 1997 he has been pursuing a Ph.D. at the Royal Institute of Technology, Stockholm, Sweden. His current research interests include wireless LANs and future wireless infrastructures for high-data-rate multimedia services.

JIANG WU (jiang@it.kth.se) is a Ph.D. student at the Department of Microelectronics and Information Technology at the Royal Institute of Technology, Stockholm. His research interests include mobile computing in the Internet, wireless network infrastructures, and IP multicasting. He received a B.S. in electronic engineering from the Tsinghua University (Beijing) in 1996, and a Licentiate of Technology in information technology from the Royal Institute of Technology in 2000.

JENS ZANDER (S '82–M '85) received his M.S degree in electrical engineering and his Ph.D from Linköping University, Sweden, in 1979 and 1985, respectively. From 1985 to 1989 he was a partner of SECTRA, a high-tech company in telecommunications systems and applications. In 1989 he was appointed professor and head of the Radio Communication Systems Laboratory at the Royal Institute of Technology, Stockholm, Sweden. Since 1992 he also serves as senior scientific advisor to the Swedish National Defence Research Establishment (FOA) He is currently scientific director of the Center for Wireless Systems (Wireless@KTH) at the Royal Institute of Technology. He has published numerous papers in the field of radio communications, in particular on resource management aspects of personal communications systems. He has also co-authored four textbooks in Radio Communication Systems, including the English textbooks *Principles of Wireless Communications* and *Radio Resource Management for Wireless Networks*. He was the recipient of the IEEE Vehicular Technology Society's Jack Neubauer Award for best systems paper in 1992. He is a member of the Royal Academy of Engineering Sciences. He is chair of the IEEE VT/COM Swedish Chapter. He is associate editor of *ACM Wireless Networks Journal* and area editor of *Wireless Personal Communications*. His current research interests include future wireless infrastructures, in particular related resource allocation and economic issues.

MAXIME FLAMENT (Maxime.Flament@s2.chalmers.se) received his M.Sc. degree (Ingenieur civil) in electromechanics from the Free University of Brussels (ULB) in 1997. In parallel with the fifth year of his engineering studies at ULB, he spent one and a half years at Chalmers University of Technology, where he received a second M.Sc. degree in digital communication systems and technology, also in 1997. His research subject focuses on air interface design for broadband wireless communication. He is currently with the Communications Systems Group at the Department of Signals and Systems, Chalmers University of Technology, Gothenburg, Sweden.