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Spectrum issues and new air interfaces

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Abstract

This is a Summary version of the propositions and ideas contained in the Draft 2001 Book of Visions (BoV) from the Wireless World Research Forum (WWRF). The findings of Working Group 4 entitled 'Spectrum, New Air Interfaces and Ad Hoc Networking' related to the two domains—Spectrum Issues and New Air Interfaces—are covered in this article. The material presented contains excerpts from the many contributions received as submissions to the five WWRF meetings in 2000 and 2001. Moreover, the views reflected here may or may not be approved by the organizations of affiliation of the authors above. It appears impracticable to name the many contributors to the work of WG4 here, since this text is a compressed version of the respective chapters of the BoV and the contributors are named there. The work related to three other domains in WG4, namely Smart Antennas, Ad Hoc Networking and Ultra Wideband systems are presented in separate articles in this journal.

Keywords: WWRF; Air interfaces; Spectrum issues; Ultra wideband; Smart antenna

1. WG4 structure of work

Wireless technology plays a vital role in providing 'continuous connectivity' between (end user) nodes and a variety of services. In a scenario where 'everybody and everything is always connected to access personalised services,' several types of 'human to human', 'human to machine' and 'machine to machine' communication links can exist, see Fig. 1.

The majority of presently used human to human information exchange is voice based. A clear shift to data services is observed. In human to Machine and Machine to Machine dialogue, the volume of information exchanged is small and a short duration 'call' at a low bit rate is usually sufficient. For human to human and human to Machine Interaction for work or leisure, the situation is quite the opposite.

Intelligent Spaces in the future Wireless World shall contain a very large number of 'intelligent' devices like wireless sensors, actuators embedded in appliances and/or carried by the living beings and interacting between themselves as well as their physical environment. In such cases, the spontaneous information exchange would be based on dynamically configurable ad hoc networks of low/very low power transceivers located in appliances with varying information-processing capabilities. The transceivers might be connected to sensors and/or actuators, like microphones and speakers. An increasing use of visual and bio-sensors and related actuators is also envisaged. The very high concentration of such transceivers would need large spectrum bandwidth. Also, some of the envisaged future mobile applications and services will be 'location aware'. This requires suitable new air interface technology capable of combining the functions of data transmission with that of precise location determination and position tracking.

Additionally, the existence of Moore's Law for bandwidth is more and more perceptible—the end users tend to embrace services and applications utilizing faster data rates ever. The service bandwidth (offered/required) is doubling every 12 months or so. The constant increase in 'users' injects further positive feedback in to the system—thus sending the BW demand spiraling up.

This potential growth scenario needs to be evaluated in the light of the following:

1. The extent of good quality radio coverage is inversely proportional to the transmitted bit rate. The cost of 'continuous' and 'all time everywhere' radio coverage

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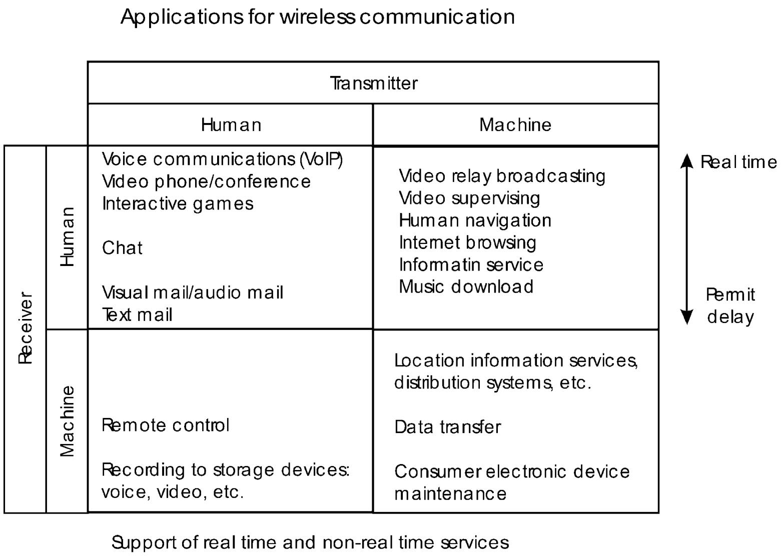

Fig. 1. Applications and users of future mobile and wireless services [Source: NTT DoCoMo].

increases very sharply with the transmitted bit rate. Moreover, additional Spectrum will be necessary in low frequency range in order to provide the required coverage in wide areas.

2. The higher the service bit rate, the larger is the required BW and the higher is the frequency range where some additional spectrum might be available.
3. The frequency spectrum assigned to radio services is used with a widely varying spectrum efficiency of the systems operated there. The regulation authorities appear to be especially restrictive when assigning spectrum for the introduction of new services, e.g. cellular mobile radio. This leads to a requirement of highly sophisticated air interfaces like those of 3G systems and the correspondingly high costs of development and deployment.
4. The economic value of a mobile radio service compared to that of other radio services and the relatively small bandwidth assigned—are apparently not considered to be the criteria of major importance for spectrum allocation.
5. The present (systems and service providers) users of the already allocated frequency bands would like to make the most out of their allocation. The absolute necessity of introduction of sophisticated mechanisms in the standardized air interfaces, e.g. space-time coding, smart antenna systems and multi-hop links to improve the radio coverage, appear to be a direct consequence of frequency spectrum shortage for mobile radio use.
6. There is a proliferation of competing information services.
7. The variety of networks for provision of seamless services in private to public and short range localized coverage to wide area coverage will be limited by the necessity of cost effectiveness of their corresponding business case.

The requirement of a very wide consensus (much more extensive than technology standardization) shall be motivated by the globalization of markets. The international regulatory frame needs to be enhanced to handle the co-existence of wireless networks operating in distinct, adjoining and partially overlapping frequency bands. In addition, the inter working of permanently established and spontaneously created networks shall have to be correctly managed. Based on the usually employed artifacts for improving the situation of spectrum congestion, the research topics addressed by this working group have been divided in the following categories:

1.1. Improved bit/s/Hz/km^2

This is achievable through improved signal design, i.e. modulation and channel coding. Well-known methods for a vast majority of wireless channels are available. The theoretical (Shannon) limit of channel capacity can be very closely approached through the use of existing mechanisms of channel coding in single input single output (SISO) channels. The system performance in multiple input–multiple output (MIMO) channels, commonplace in wireless communications, can be greatly enhanced by use of Space Time coding, multi-user detection and smart antenna techniques. However, signal design for very high bit transmission (100 MB/s) in difficult wireless channels (e.g. for fast moving mobiles) is still an open issue. So is the case for providing throughput like 1 GB/s for the 'hot spots'. Information Compression, i.e. signal processing and source coding techniques useful to reduce the source output bit rate so that a larger number of simultaneous calls are accommodated per unit BW, is well mastered for voice sources. More efficient algorithms for multi-media services are currently being developed.

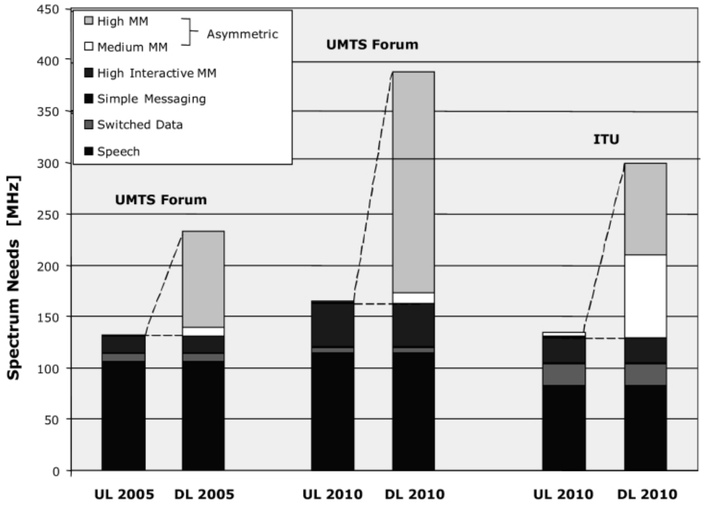

Fig. 2. Projection of the future usage of IMT 2000 systems (Source: UMTS-Forum, Report No.6 and ITU-R Report M.[IMT.SPEC]).

1.2. Refined multiple access techniques

The ability to accommodate several users, accessing a given service, simultaneously in a communication channel can go a long way to improve the situation of spectrum usage. The presently deployed 'contention free schemes' are well mastered. Further improvement through the use of 'contention based (or tolerating) multiple access schemes' for packet mode communication are possible. Simultaneous implementation of adaptation mechanisms at different layers of the protocol stack should be helpful in improving the system performance all the while allowing for fine granularity of spectrum usage for different mix of services (channel or packet switched).

1.3. Short range spontaneous networking

A naturally existing trade-off between the transmitted power and the improvement of efficiency in the use of the radio spectrum can be exploited through applications of ad hoc networking of wireless capable nodes. Body area networks (BAN), personal area networks (PAN), networking between appliances at home and office and wide area networks of permanently installed and/or mobile nodes shall be instrumental in bringing about the success of 'everything, everybody always connected' idea. Also, technical issues for all the protocol layers need to be considered. A non-exhaustive list is provided below:

- Medium Access Control Layer; Centralized vs. Distributed, Fairness, Quality of Service (QoS) Support, Varying Node Capabilities;
- Management of Spectrum vs. Device Resources (Transmit Power, Processing);
- Network Layer: Addressing, Routing, Mobility and Topology Management;
- Auto-configuration: Service Discovery, Network Dynamics.

Authentication, Authorization and Accounting and Information Security and User Privacy.

Additionally, it can be expected that such an evolved Wireless World would require new arrangements for managing the rare physical resource namely the radio spectrum. Hence the following category of topics needs to be duly addressed.

1.4. System co-existence and radio network interworking

A large number of wireless technologies for varied applications exist and several new technologies are being developed. Moreover, multiple existing wireless technologies are being improved for their field of application. The introduction of digital audio broadcast (DAB) and DVB or the introduction of EDGE are a few examples. It has been proposed to develop an approach based on dynamic spectrum re-farming so that the use of radio spectrum below 1 GHz for cellular and mobile communications be maximized. It is expected that more efficient use of spectrum through system overlay and temporary allocation shall be achievable. Recommendations for spectrum sharing for the co-existence of several technologies and different applications need to be formulated through the comparison of efficiency/complexity trade-offs.

2. Global vision and the related issues

2.1. Asymmetric traffic characteristics of uplink and downlink usage

The higher the transmit rate of a service the higher is the expected asymmetry of usage of the uplink and downlink channels, making the downlink a bottleneck. Both, UMTS Forum and ITU-R have published a projection of the future usage of IMT 2000 systems and have identified the spectrum needed for the specific services, see Fig. 2. A substantial

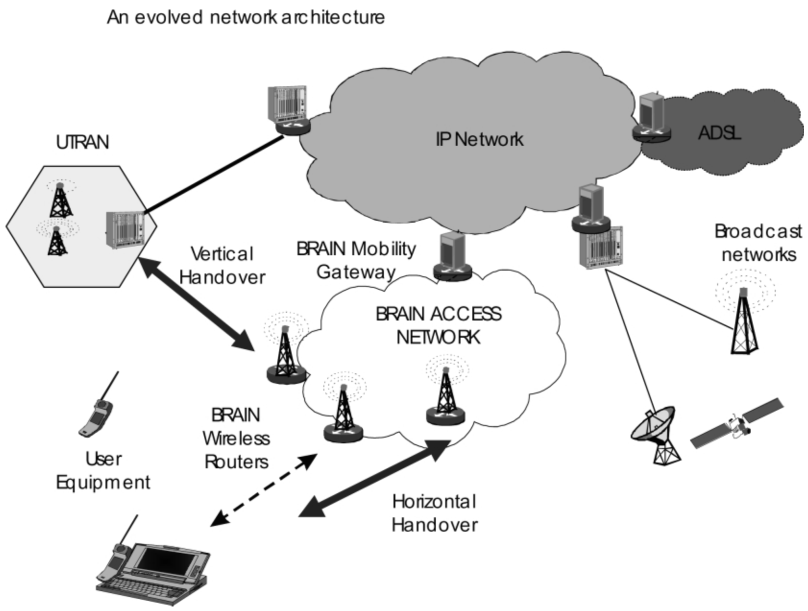

Fig. 3. Hybrid network architecture studied in the IST/BRAIN project.

asymmetry of the expected average traffic has been predicted: especially for medium and high data rate multimedia traffic.

A possible solution could be based on further development of 3G systems for supporting higher bit rate services on the downlink than on the uplink. This could be achievable, e.g. by allowing a variable duplex spacing and multiple FDM channels for parallel usage on the downlink.

It has been proposed to combine cellular radio and digital broadcast services into an integrated system to make use of the high downlink capacity of broadcast systems as part of communication sessions initiated via cellular radio. Experiments have proven the design to be feasible but to have a limited flexibility owing to the MPEG-2 container used for data transmission in the DVB-T standard. Per DVB-T (8 MHz) channel a total data rate of 12 MB/s has been demonstrated. A capacity improvement of the combined system could be realized, especially, for broadcast type of applications of UMTS. This is not of much advantage for point-to-point communications due to the large TV broadcast cells and the resulting small capacity. A homogeneous system where UMTS instead of DVB-T is applied on the 8 MHz TV-channels could be much more attractive. Here the requirement of dual mode user terminals, operating in completely heterogeneous systems, shall be eliminated. The downlink in the broadcast band could be implemented by all the base stations of a cellular operator in a coverage area (instead of the TV-towers only). This will allow a much higher capacity gain through cellular spectrum re-use and location specific broadcast contents.

Dynamic channel allocation to provide UMTS downlink on TV-channels shall have to be based on a concept called co-farming of spectrum [8]. Hence, both the broadcast operator and the cellular operator could be guaranteed a mutual benefit. Further, the UMTS standard would need to be extended to allow various duplex spacing and multiple downlink channels.

2.2. Wireless LANs for broadcast and asymmetrical traffic support

Wireless LANs have been proposed to complement the capacity of 3G systems and have been studied, e.g. in the IST/BRAIN[1] project [7,10]. The co-operation of cellular and WLAN through a common core network coupled with the use of a multi-mode terminal controlled by a common mobility management function accessible via any of the access systems shall enable the provision of the best possible service at a given location, see Fig. 3. The figure also includes broadcast networks as described earlier.

The concept of BRAIN is to provide broadband services in so-called hot spots where a WLAN based pico-cellular radio coverage is available. The BRAIN project proposes the implementation of horizontal handovers, e.g. across access points providing broadband access and vertical handovers between the two different access networks.

The WLAN might be based either on ETSI/BRAN HiperLAN/2 (H/2) or IEEE 802.11. Systems combining 3G (UMTS) and WLANs are expected to come into operation in Europe during the present decade.

This would complement the integration of radio based systems like DAB and DVB-T [4], besides PAN like Bluetooth into a common network architecture as shown in Fig. 4 [10]. Radio interfaces developed specifically for various speeds of mobility and classes of service will be combined as access networks and connected to a common core network so as to provide universal mobile access for all

[1] Information Society Technology, Broadband Radio Access to IP Networks.

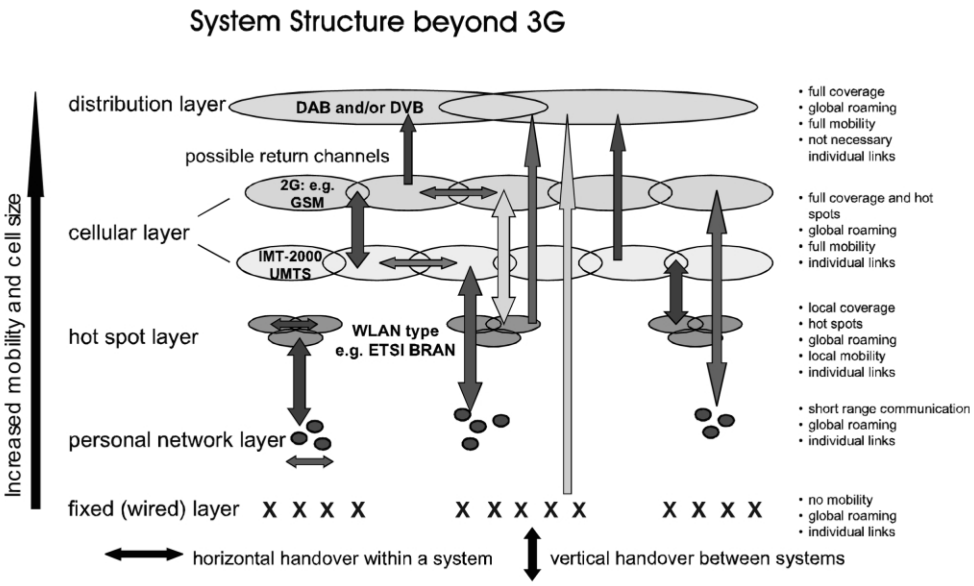

Fig. 4. Layered architecture of an integrated radio network comprising digital broadcasting, 2G and 3G cellular, WLANs in hot spots and PAN [1].

services known in fixed networks. This system should be able to support any class of traffic (point-to-point, point-to-multipoint (PTM), broadcast) by exploiting the most appropriate air interface in spectrum- and cost-efficient way.

2.3. Air interfaces

Experience from the past has shown that the idea of an universal system able to cover all the needs of wireless and mobile applications cannot be realized. Instead, a multitude of air interfaces will be applied in the future to cover the specifically different needs of mobile and wireless (slow-moving) communicating users in the various usage scenarios.

Multi-mode terminals will be a must. Such terminals should be able to hook-on to the best-suited air interface from a number of available interfaces in a given environment. Both the traffic performance and cost shall be considered. Several points related to the implementation of multi-mode terminals are covered in the BoV, Chapter 2.3 on re-configurable (software defined) radio terminals. To get an understanding of the issue, Fig. 5 shows some of the criteria to be considered when applying a multi-mode terminal to serve a mobile user in an optimum way [9]. The characteristics of service provisioning, the class of service and the cost will be the main decision criteria for the use of one of the multiple air interfaces available from the same or a number of competing operators. Further details include:

- availability under the current conditions of terminal movement, e.g. radio coverage,
- real time constraints of the service to be performed, e.g. instantaneous, when demanded, semi-instantaneous, e.g. provisioning within a given time window,
- cost of service per time unit/or information unit,
- QoS, e.g. real-time requirements in terms of delay and delay jitter for an interactive service, transmit data rate required,
- service management, i.e. ease of use of services across different radio networks, supported by the terminal and the operators.

The two buttons shown at the terminal represent the internal functions that decide which radio network to use for a given service under the available conditions.

The multitude of air interfaces addressed as natural representations of the systems shown in Fig. 4 provides sufficient motivation for engaging in research towards more unification in order to simplify the terminals. This would require the study of air interfaces able to cover two or more application areas in a specific cost-efficient way. Besides this goal a demand for higher speed data transmission with mobile radio systems of 100 MB/s and 1 GB/s for slow mobile terminals has been expressed [2].

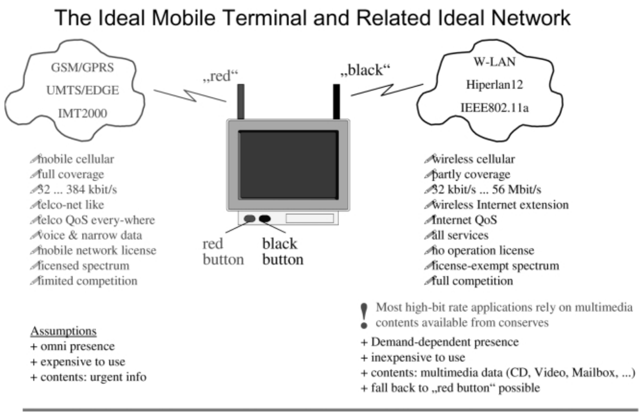

Fig. 5. Multi-mode terminal of a radio network with multiple air interfaces [9].

3. Considerations for spectrum related issues

3.1. State of the art and open issues

At present, strategies for handling interference between different radio systems typically assume a fixed allocation of frequency bands to operators and/or services, with sufficient guard band (Minimum Frequency Separation) between neighboring spectra, and a set of rules for spectrum usage (Frequency Sharing Rules) [3]. Based on this assumption, the evaluation of the efficiency of these strategies is done by modeling the interference phenomenon together with statistical analysis of the models, to obtain, for example, a prediction of the probability that interference will cause unacceptable degradation to either of the services. Such studies have been performed for special cases (UMTS vs. DECT, GSM vs. TETRA) [5]. Analysis of the interference situations and the related prediction of the QoS for a given guard band have been presented.

Present strategies have some shortcomings, especially with respect to spectrum efficiency:

- Almost all radio systems experience time-dependent load characteristics. Most services, for example, have a certain, predictable load pattern over the course of a day, with peak times and low-load periods. With statically assigned spectrum, these systems have to be designed for peak load QoS. However, most of the reserved spectrum will be unused for long periods of time. Dynamic allocation of spectrum will enable the use of these unused resources for other services, which might face a shortage of bandwidth at that moment.
- Spectrum efficiency can be increased by choosing the optimal transmission technology for a given load scenario. For example, data can be transmitted both via a point-to point UMTS link and a broadcast DAB link. In a scenario where several mobile users are requesting the same data, transmission via the broadcast service will be more efficient, as otherwise several point-to-point links will use bandwidth to transmit the same data over different dedicated radio channels.
- Intelligent systems capable of detecting or predicting interference, shall be able to avoid impaired channels in situations were interference really occurs. Thus spectrum that was reserved for guard band can partially be used, thereby freeing additional spectrum for communication use.
- Existing systems cannot exchange information on their respective spectrum usage. It can be expected that co-operative allocation of spectrum can significantly decrease the need for guard bands, by allowing the systems to negotiate what parts of the impaired spectrum between the two services is used by which service.

These advances have to be supported by detailed studies on the impact of dynamic spectrum allocation on the interference between the different radio technologies integrated into one communication system. It can be expected that the type of radio technology using a given part of the spectrum strongly influence the level and spatial distribution of the interference emanating from this portion of the spectrum. It can be expected that, through exploitation of statistical multiplexing and the optimized assignment of minimal guard bands, the overall spectrum efficiency of the operating services will be increased considerably.

4. New air interfaces

4.1. Issues to be addressed in the future

Today, radio networks operate with fixed long-term spectrum allocations. Systems like the global system for mobile communication (GSM) are available all over the world in exclusively allocated spectrum. The same will hold true for the universal mobile telecommunication system (UMTS) [9] when it will be introduced. However, the required spectrum varies both over the time and over the location. For example, in many regions there is more demand for mobile voice and data communication during business hours than during leisure time. The same relation is often seen between crowded business centers and sparsely populated areas. The actual required spectrum for a radio service changes with time and location. Therefore it is worth investigating a dynamic allocation of spectrum [1]. Note that this reasoning is based on the aggregated user requests; individual requests can be demanding, of course, irrespective of time and location.

Overall, the multi-radio system approach to use spectrum resources more efficiently addresses the co-operation of different radio systems, preferably in a common frequency range combined with dynamic spectrum allocation. We see a need to address all these issues within one approach because it is already clear that the existing spectrum allocation for mobile communication services is not sufficient while considering the tremendous growth rates for this type of communication. Hence for all additional services, new spectrum has to be made available. However, a fixed and worldwide allocation is difficult if not impossible to achieve, but a dynamic allocation could possibly open a lot of regional spectrum capacity. In addition, from a system and especially from a terminal design perspective, the closer two services are in allocation in a common frequency range, the easier is the co-operation for dynamic spectrum management. This holds especially true for UMTS and broadcast services supporting mobile users like DVB-T—these are points of main interest for investigations in Europe.[2]

[2] This convergence is applicable to other digital TV standards, as well like ATSC DTV and ISDB-T.

4.2. The vision and the issues

Whereas 1G and 2G mobile systems were initially designed mainly for circuit switched (CS) communication (like voice), in 3G efficient solutions to handle both CS and packet switched (PS) services have received a great deal of attention. As PS services are in general, e.g. more delay tolerant but require better residual error rates than CS services, new air interface and network solutions had to be developed for cellular systems with good spectral efficiency. In addition to the ability to efficiently handle both CS and PS services, another important design target of 3G systems has been to provide efficient support for applications requiring simultaneous transmission of several bit streams with possibly different QoS targets. All this has called for very flexible air interface and network solutions.

Although 3G systems represent clear improvements over 2G systems in terms of spectral efficiency, peak data rates, QoS control, etc. work is already on-going on developing the systems even further. One of the first steps has been to define innovative solutions for improved packet access performance especially in downlink (from network to user terminal) direction. This is quite natural as it is anticipated that traffic volumes in downlink will be bigger than in the opposite (uplink) direction. An example service, which follows this assumption, is web browsing which is more downlink intensive. At the same time there has also been a lot of attention on network evolution, which is heading towards IP-protocol based solutions.

Even though 3G and its evolution is expected to continue for several years, there is a visible need to consider other (possibly) revolutionary air interfaces. By dropping out the backwards compatibility requirements with current and future 3G systems there is more room for new innovations which could lead to a substantial increase in system capacity and capabilities. It should be noted, however, that any beyond 3G revolutionary solutions must be clearly better than evolved 3G in order to justify any technical or commercial interest. Therefore, the targets for future wireless research must be set considerably higher than the anticipated capabilities of evolved 3G systems.

4.3. State-of-the art in 3G

The two most prominent 3G systems, WCDMA as specified by 3GPP [11] and cdma2000 as specified by 3GPP2 [6], are both based on direct-sequence code division multiple access (DS-CDMA) access scheme. Thus it is quite natural that they employ very similar radio transmission solutions. The key features that contribute to the overall good performance of those 3G systems include:

- efficient channel coding, rate matching and channel multiplexing solutions;
- various diversity techniques;
- beam-forming;
- link adaptation techniques;
- shared channels for PS communication (only in WCDMA).

Flexible combination of channel encoding, rate matching and channel multiplexing allows the radio interface to efficiently utilize only the needed radio channel resources to get the desired QoS. Different transport channels[3] with (possibly) different QoS characteristics can be efficiently multiplexed into either single or multiple physical channels. Varying energy-per-bit requirements of different transport channels are handled by rate matching function which, by using repetition or puncturing, matches the channel encoded bit stream to the available bit rate of the physical channel. As a result the physical layer can efficiently handle various bit rates with no (repetitions) or little loss (puncturing) in performance.

Due to the inherent properties of CDMA, 3G systems can utilize various different diversity techniques including:

- Multi-path diversity;
- Macro-diversity (soft handover);
- Time diversity (ARQ);
- Rx diversity (mainly uplink, but can be used also in downlink);
- Site selection diversity transmit power control (SSDT, only in WCDMA);
- Both open and closed loop Tx diversity techniques.

Use of wide variety of diversity techniques is one key reason for improved performance of 3G radio when compared to 2G radio.

3G air interfaces have got built-in support both for fixed and steerable beam concepts. In, e.g. WCDMA network tells the mobile terminal which signal (primary common pilot, secondary common pilot or dedicated pilot) can be used for channel estimation in downlink. As dedicated pilots are specified even user specific beams are efficiently supported.

There are two main link adaptation techniques in 3G systems: transmit power control (TPC) and ARQ. TPC includes both open loop and closed loop solutions with an obvious goal of trying to minimize the Tx power yet keeping the target received signal quality level. The closed loop TPC can be further split into inner and outer loop control. The maximum rate of closed loop TPC depends on the frame structure of the physical channels. For example in cdma2000, TPC rate is 800 Hz.

Another (implicit) link adaptation technique included in the current 3G systems is Type I ARQ operating between data link layer protocol entities. Erroneously received data packets are discarded at the receiver end and retransmitted from the transmitter side. This

[3] In WCDMA standard *transport channels* define the interface between L1 and Medium Access Control of L2.

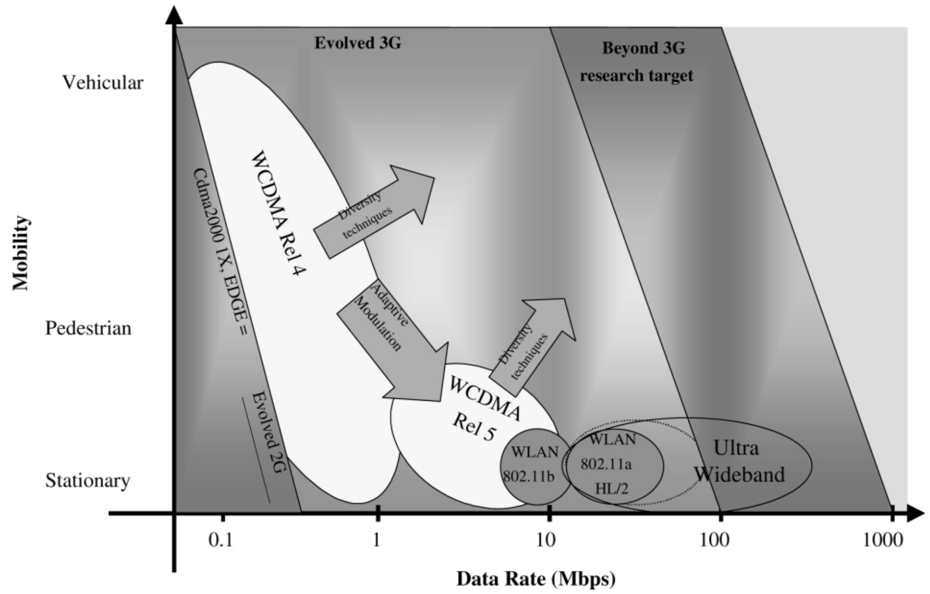

Fig. 6. Mobility vs. data rate (Source Walter Hirt, IBM Zurich 2001).

provides automatic adaptation to local channel conditions as only 'bad' packets need to be transmitted again.

Finally, WCDMA system employs also so called shared channel concept both in downlink and uplink (TDD mode only) directions. The basic idea is to schedule several packet users simultaneously on a single physical channel. This leads to efficient utilization of channelization code space and also improved throughput for PS services.

4.4. Research for future wireless

When 3G was initially envisioned in the early 90's, it was not very clear what its breakthrough characteristics would be. The only self-evident requirement was that 3G must offer much higher data rates and higher traffic capacity than 2G. Soon after the initial deployment of 2G the goals and targets of 3G were better understood and the research and later on standardization work could really start.

Now that the first 3G systems are being built it is natural to start asking what could be the next big step. The situation today with respect to 3G and what might come after it is not quite the same as with 2G and its successor 3G 10 years ago. In many ways step from 2G to 3G was bigger than step from 1G to 2G. In 3G there is a lot of built in flexibility and extension possibilities so that it can evolve for long time and be able to provide a wide variety of different kind of services to the end users. Therefore, it is not clear what any beyond 3G system could or should offer. In fact, it is a possibility that we will not see a full blown new mobile system generation after 3G. Maybe we will only witness the emergence of new radio access schemes that can then be connected to a 3G network.

As 3G evolution seems to be going towards 10 Mb/s with 100 Mb/s peak data rates, any 'Beyond 3G' air interface should be clearly better in order to justify its technical and commercial feasibility. Fig. 6 shows the mobility vs. data rate both for different mobile system generations and also the research target for a possible revolutionary Beyond 3G air interface. There are several reasons why we should set the challenging Beyond 3G research targets of up to 100 Mbps and 1 Gb/s peak data rates for wide area coverage full mobility and local area coverage low mobility cases, respectively. These include:

- 3G will go towards 10/100 MB/s (wide/local area)—beyond 3G should be clearly better
- No application may need that high continuous bit rates but the system may need it in order to
  - Serve many high bit rate users simultaneously;
  - Maximize throughput/capacity;
  - Minimize latencies.
- There may be an optimum bandwidth that maximizes the spectral efficiency of a wireless system
  - Research target must be set high to 'capture' that optimum
- Short distance radio bit rates will go towards 1 GB/s and users could expect wide area coverage service rates to be fairly close.

Even though the 100 MB/s and 1 GB/s peak data rate target is very challenging it could be achievable. Given the very challenging goals and expected long evolution path of 3G a commercial launch of any Beyond 3G air interface could be possible in year 2010 or later.

How to reach the challenging goals presented here for Beyond 3G air interface is a question for international research community. Yet, we can list some potential research areas that need to be covered as part of Beyond 3G air interface studies including:

- Spatial domain solutions including Tx/Rx diversity, beam-forming, MIMO systems;
- Multi-dimensional adaptation (time, frequency, space);
- Multi-dimensional radio resource allocation (code, time, frequency, space);
- Error correction coding.

Spatial domain solutions are very important if considerable improvement in wireless system performance are targeted for. Thus, techniques like Tx/Rx diversity, beam forming and MIMO should be studied carefully—both with shorter (e.g. evolution of 3G) and longer term goals (possible Beyond 3G solutions) in mind. In terms of capacity improvement spatial domain processing is probably the most important research area to consider.

Adaptation in general tries to optimize the performance of a single radio link. Well-known adaptation in time domain could be further extended to frequency and spatial domains. Expected gains in system (and link) level performance need to be evaluated in comparison to those reachable by multi-antenna solutions.

Already in 2G/3G radio interfaces it is possible to perform radio resource allocation in code, frequency and time domains. Note that in 3G systems like WCDMA, spatial domain is indirectly exploited as the cellular throughput depends on the scheduler algorithm and decisions to allocate resources to a mobile terminal may depend on its location. Further improvements could be available by adding the possibility for fast scheduling also in the frequency domain.

With the advent of Turbo coding the performance of error correction coding solutions have approached quite near the Shannon channel capacity limits. Thus, big improvements from a single link point of view are not expected. However, the achievable gain in performance by-combining channel encoding with various diversity and multi-dimensional adaptation techniques needs to be evaluated.

5. Design example of low power, high capacity, mobile broadband system with invisible base stations

Following is a list of requirements, desires, visions and possible options for a future Mobile Broad-band System. It is clearly apparent that a vast amount of research efforts are needed to make such a system happen:

- Improved bit/s/Hz/km^2 high capacity, low power air interface with advanced multiple access techniques;
- High spectrum bandwidth for high bit rate (100/1000 MB/s) services;
- Co-existence with other systems operating in the same band;
- Interworking and/or integration with existing systems;
- Ad hoc networking ability;
- Support of broadcast and of asymmetrical traffic;
- Extensive use of smart antenna array systems;
- Support of terminal mobility up to, say, 60 km/h;
- Acceptance of the visible radio network infrastructure by the citizens;
- Small base station transceivers, e.g. 300 cm^3 including antenna system ('non-visible'), mounted on lamp posts or below roof-top at buildings with mains supply;
- Extensive use of the relay (multi-hop) concept to reduce the number of broadband cable ports to the fixed network;
- Use of radio relays (multi-hop) to improve radio coverage, capacity and system availability, e.g. indoor radio coverage via in-band radio relays.

◆ Extensive use of out-of-band radio relay for inter-connection, e.g. to the fixed network.

It appears necessary to develop a new type of system that goes substantially beyond what is technically feasible today.

An example design of the system shown in Fig. 7 is based on pico base stations that are connected by fiber (dashed lines), possibly using radio over fiber, to the point of presence (POP) of the fixed telecommunications network.

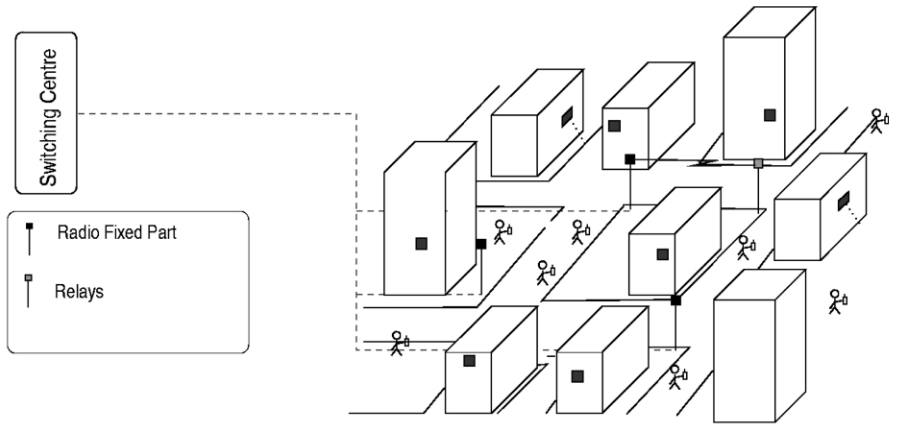

Fig. 7. Base stations of a mobile broadband system fed via fiber [9].

Also the flash sign contained in the figure shows a possible relay link to connect base stations via a multi-hop radio link to the fixed network. In densely populated small coverage areas, it is possible to provide broadband Internet access and simultaneously satisfy the requirement of low radiated power.

Apparently, it is possible also to connect the pico base stations via PTM line-of-sight (LOS) radio to the POP of the fixed telecommunications network as shown in Fig. 8. Since a LOS radio system has a limited capacity only, a tandem of two air interfaces each one in its respective frequency band shall be implemented—one for the LOS system and the other one for the mobile broadband system. The LOS system capacity is made available to the pico base stations only as required.

The radio exposure, resulting from pico base stations, of humans (outdoors or in buildings) will be quite small compared to the present day systems. The radio power used to connect a mobile terminal to a pico base stations will be very small, too.

Radio coverage in buildings might be provided through radio relays mounted on windows and illuminated from outdoors. The dark colored squares shown at the buildings represent these relays. High gain antennas might be used to connect base stations and their relay nodes.

To connect to the PTM LOS radio system, pico base stations are expected to use high gain antennas.

The PTM LOS system might use high gain antennas also to connect to pico base stations, transmitting in-band or out-of band. The radio exposure of humans from the PTP LOS radio system thereby can be kept very small. The PTP LOS microwave radio network above roof-tops will apply highly directive antennas and the radio exposure of humans will therefore be very small.

Being mounted on the existing infrastructure and due to their small size, the pico base stations will be nearly invisible Pico base stations will provide broadband (> 100 MB/s) radio access to mobile users. A second layer of micro- or macro-cells will be overlaid to the scenario shown in the Figs. 7 and 8 using the same air interface as being used in the pico cells. Existing (visible) base stations might be used to carry the related antenna systems. The pico-cellular broadband radio network introduced here might instead be supplemented by the existent cellular mobile radio networks. The high speed air interface between pico base stations and mobile terminals will have to be developed. UWB and multi-carrier CDMA could be two of the candidate transmission techniques for this purpose. The concept of pico-cellular radio networks heavily relying on relay nodes has been described in Ref. [9, pp. 724–727] and the concept of the Wireless Media System has been introduced in Ref. [9, pp. 742–743, 1034–1041].

6. Proposed research tasks

The Book of Visions 2001 contains details on a large number of proposed research tasks in the domains covered by WG4. These tasks are not explained in detail here in order to keep this article of reasonable length. The list below should be helpful in providing links to different chapters of the BoV.

- Spectral Coexistence of TDMA/FDMA and CDMA Systems;
- Frequency Etiquettes and Spectrum Sharing Rules for WLANs;
- Spectrum Exploration for Mobile Radio;
- Smart Antennas;
- Location—Sensitive Radio Resource Management;
- Ultra Wideband (UWB) Radio Technology (UWB-RT);
- Multi-Carrier based Air Interface;
- Multi-Hop Ad hoc Networks;
- Radio Propagation and Network Planning.

WWRF plans to elaborate further on the BoV to generate an upgraded edition in 2002 and possibly even beyond.

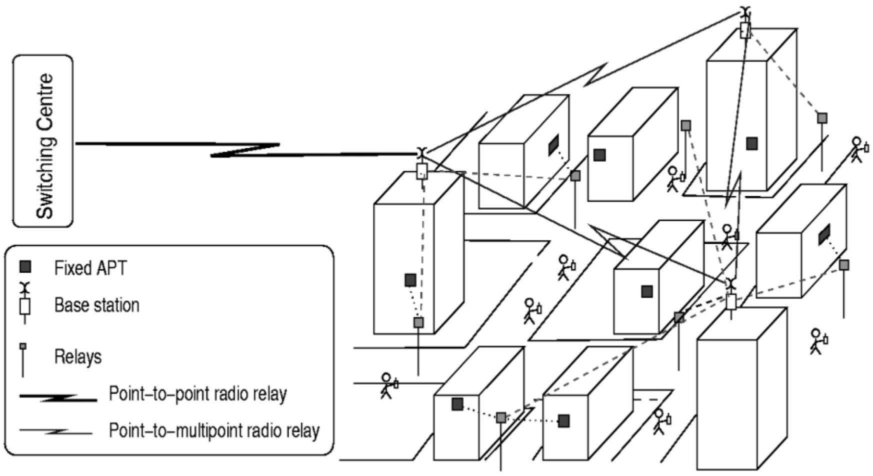

Fig. 8. LOS Radio to connect Pico-Basestations to the Fixed Network [9].

Acknowledgments

The material presented here reflects the ideas and opinions of numerous individuals that contributed to the BoV by means of submissions to the WWRF meetings in 2000 and 2001. It is impossible to name them here. Their contributions appear in the appendix of the BoV.

References

[1] U. Horn, R. Keller, N. Niebert, Interactive mobile streaming services—convergence of broadcast and mobile communication, EBU Technical Review (1999) 14–19.
[2] Wireless World Research Forum, Book of Visions, Draft 2001, see www.wireless-world-research.org.
[3] Radio Research Laboratory, Motorola: an etiquette for sharing multimedia radio channels, ETSI RES 10/TTG-94/98, September.
[4] U. Reimers, Digital video broadcasting—current status, future developments, IEEE Multimedia Newsletter (1996) 8–11.
[5] M. Lott, M. Scheibenbogen, Calculation of minimum frequency separation for mobile communication systems, In Proceedings of the Second European Personal Mobile Communications Conference (EPMCC '97), Bonn, Germany, September 1997, pp. 133–137.
[6] TIA/EIA/IS-2000, cdma2000 Standard for Spread Spectrum Systems, 30 August 1999.
[7] J. Urban, D. Wisely, E. Bolinth, G. Neureiter, M. Liljeberg, T.R. Valladares, BRAIN—an architecture for a broadband radio access network of the next generation, Wireless Communications and Mobile Computing 1 (2001) 55–75.
[8] B. Walke, Spectrum issues for next generation cellular, Proceedings of Visions of the Wireless World, Workshop of the Wireless Strategic Initiative, December 12, 2000, Brussels, Belgium.
[9] B. Walke, Mobile Radio Networks—Networking, Protocols And Traffic Performance, second ed., Wiley, Chichester, UK, 2001.
[10] W. Konhäuser, Innovating the mobile world beyond the third generation, Proceedings of Visions of the Wireless World, Workshop of the Wireless Strategic Initiative, December 12, 2000, Brussels, Belgium.
[11] 3GPP, Physical Layer—General Description, 3GPP TSG-RAN Technical Specification, TS 25.201 v 4.0.0, 15 p.