Nico Baken, Edgar van Boven, Frank den Hartog, and Ramin Hekmat

A Four-Tiered Hierarchy in a Converged Fixed-Mobile Architecture, Enabling Personal Networks

We present a new way of capturing the future technical infrastructure of a converged fixed-mobile infrastructure by means of a four-tiered hierarchy of one fixed and three different mobile and wireless (access) layers. With such a view, the current range of heterogeneous interconnected public and private networks can be easily modelled as a landscape of pockets (the mobile/wireless networks) with various depths and widths, connected by a drainage of high capacity (the fixed network) in which marbles (information) find their way. The metaphor clearly illustrates that higher demand for mobility will increase the need for a densely distributed high-capacity fixed access network. It also shows the high potential of the relatively new concept of *personal networking*. In the light of this model, we describe crucial technologies for fixed-mobile convergence, such as handover, roaming, and gateways. Summarising, we believe that our contribution in this paper could prove to be a helpful guideline to the telecom industry both from a strategic and operational perspective.

Authors
N. H. G. Baken
KPN Telecom and Technical University of Delft
Regulusweg 1, 2516 AC The Hague,
The Netherlands
Email: n.h.g.baken@kpn.com or
n.h.g.baken@ewi.tudelft.nl; Tel: +31 70 343 9137

Edgar van Boven
KPN, Operator Fixed Network
P.O. Box 30000, 2500 GA Den Haag,
The Netherlands
Email: e.f.m.vanboven@kpn.com
Tel: +31 70-3434797

Frank T. H. den Hartog
TNO Telecom
Brassersplein 2, P.O. Box 5050, 2600 GB Delft
The Netherlands
Email: F.T.H.denHartog@telecom.tno.nl
Tel: +31 15 285 71 19

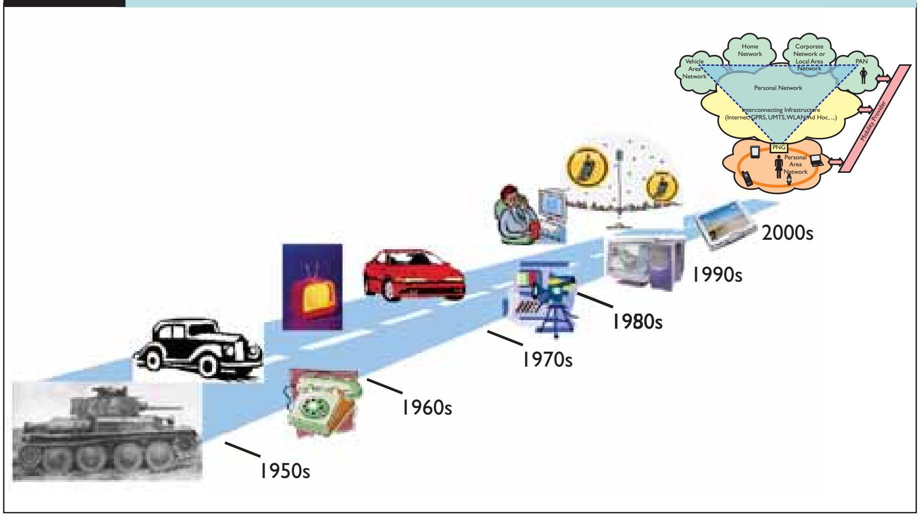
Ramin Hekmat
Delft University of Technology
Electrical Engineering, Mathematics and Computer Science,
P.O. Box 5031 2600 GA Delft
The Netherlands
Email: r.hekmat@ewi.tudelft.nl
Tel: +31 15 278 6272

Introduction

Within the realm of the ICT world we can distinguish some clashes of beliefs in different technologies. We witnessed the clash between the 'net-heads' and the 'bell-heads'. By the way, is this fight over? Was it a non-issue? Now it looks as though a new non-clash/issue is emerging: the clash between the fixed and mobile believers. Although we do not have the arrogance to prevent this clash by giving some insights into this matter, we embark with this paper on a fundamental endeavour. As an introduction, we have to go back in recent history (Figure 1).

Directly after World War II, the world was 'shaken', and people craved to find new certainties corresponding to the lower Maslow layers: housing, food, security, jobs, and getting the economy restarted. This building phase in the 1950s created the

Figure 1 The road towards personal networks

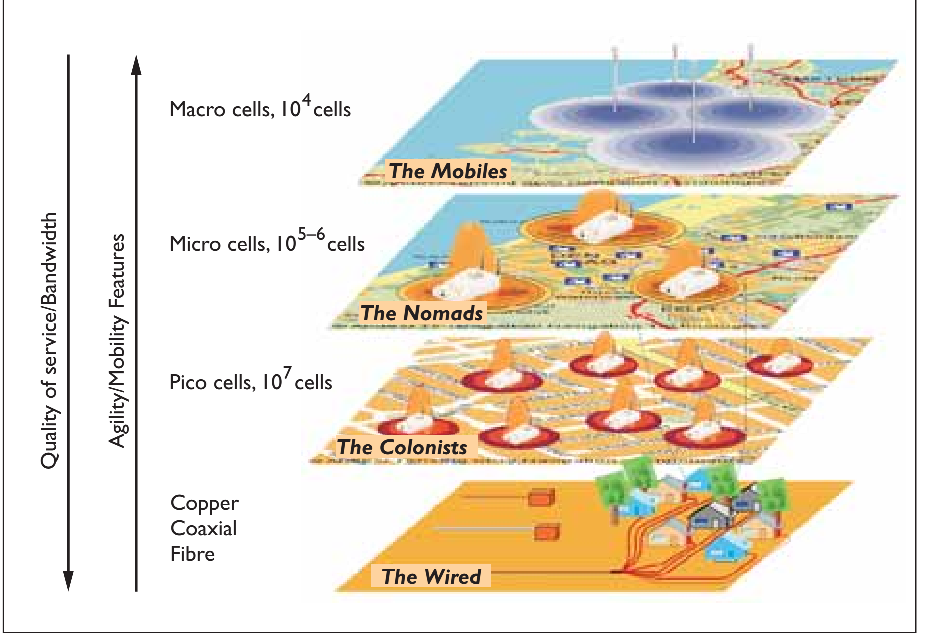


conditions for prosperity. In the 1960s and 1970s, the plain old telephony service became a reality for nearly all families in the Western world, and, in the 1970s and 1980s, the same became true for the automobile, enhancing physical mobility tremendously. Now combining the latter two developments explains retrospectively the unpredicted and vast success of mobile telephony in the 1990s. To technologically realise mobile telephony, operators rolled out, in Europe, the second mobile generation; that is, the GSM networks. In The Netherlands alone, some 5000 GSM masts were erected to cover the whole of the country, creating large radio say macro-cells (with a radius in the order of several kilometres), which can be interpreted as large electromagnetic extensions of a fixed (access) network; this with the aim to cover all those areas, firstly along highways where obviously the fixed access networks were not nearby. Thus the mobile customers, say the 'mobiles', were enabled to make their voice calls 'on the move'. In that same decade of the 1990s, we see the gradual appearance of stand-alone PCs in nearly every home, and, after 1995, the rise of the World Wide Web and the phenomenon of getting online all these PCs, and, as a latest trend in our decade, the explosion of broadband services for the residential customer based on DSL- and cable modems.

Add this all together and we will see the inevitable birth of the *personal network* (PN). However, the users of PNs will be most of their time a 'colonist' or 'nomad'†, and the latter will be topographically often in urban areas where the fixed network is near, this contrary to the early 'mobiles'. This means that the 'electromagnetic extension of the fixed network' can be smaller for the first two categories: the radio cells for them can be smaller, but require more 'bandwidth power'. Thus, we could roughly associate the three user groups with pico, micro and macro radio cells (see also further on) on layer two, three and four in Figure 2, which gives a rough draft of a four-tiered hierarchy of future networks. All three cell types are connected to the fixed network, but the connection differs in terms of bandwidth.

The authors believe that the future technical infrastructure of a converged fixed-mobile infrastructure can be captured in a four-tiered hierarchy of one fixed and three mobile (access) layers. Recognising the subtle interdependency between distance, bandwidth and quality of service (QoS), we conclude that obviously the radio cells need to become smaller with the increasing demands for personal networks and their growing needs for broadband applications. Combine this with the requirements for real-time services and the complementarities of the fixed and mobile networks becomes fully evident: *Mobility is a crucial service feature and the more (broadband) mobility will be required, the smaller the radio cells and the more fixed access network capacity, that is, bandwidth, will be required. In the end we will see therefore ether over fibre!*. The first signs of the latter can be seen in Reference 1.

Figure 2 Four-tiered hierarchy of the future network



We distinguish four layers. The bottom layer can be associated with the fixed access network, on top of that three layers with different mobile and wireless access technologies. In the picture of the 4-tiered hierarchy, it is denoted that the QoS will increase for a given service in the downward direction. This may not yet be the case but will be a fact once micro and pico cells are standardised and have levelled their maturity with that of the macro cells.

The end-user, depending on his/her role (employee, member of a community, etc.) plus his/her location, will be able to gain access to his/her personal network, whereby authorisation will be granted on the basis of something the user possesses, knows and is. Continuity of the service can be maintained internationally through seamless vertical and horizontal handover across and in three mobile layers delivered by service provider packagers using again a four-layered business model.

In the first mobile layer we will see, in The Netherlands, some 10 million pico cells, in the heart of which we find an integrated access device (IAD) that will be either directly connected to the fixed network or via a host of 100 000 public Wi-Fi cells on layer three. The IADs connect wireless the majority of devices in-house and in-office.

Increases of agility concur with the higher layers. In the top layer we will see the largest mobility at the cost of quality of service (QoS) and bandwidth. This top layer will consist of some 10 000 UMTS cells. Mixing these ideas with the fact that in The Netherlands alone we will, say in 2012, see some 10 billion devices of which the vast majority will be passive RFIDs, some interesting technical challenges will need to be met to cope with all the traffic interlinking business, residential customers and devices. In this paper, we place the different technologies in perspective, highlight the concept of PNs and elucidate the concepts with some metaphors.

Explanation of the 'Marbles and Pockets' Metaphor

About a decade ago the existence of 'mobile only' operators absolutely made sense. It took only five years to turn mobility features and personalised communication into commodity. Narrowband GSM voice services proved to be an unforeseen gift, fundamentally changing human behaviour. It would not have looked the same if a GSM conversation had required a lot of precious bandwidth (for example, 2 Mbit/s). And

† The agility/mobility of a user increases from colonist, via nomad to mobile, whereas their need for broadband services decreases.

here lies the relation with the following statement: 'Mobility is a crucial service feature, the more (broadband) mobility, the smaller the radio cells, the more fixed access network capacity will be required. In the end we will see *ether over fibre*.' This statement's final chord refers to the envisaged future situation in which fibre will be widely deployed in the local loop. On the other hand, future end-user devices will dominantly become wireless. Merging these two leads gives the image of radio bearers (ether) connecting mobile end-users to a fixed local loop outlet (fibre), irrespective of whether this is public or private infrastructure. Transport of bits over radio bearers is, in general, more expensive compared to deployment of fixed bearers, especially when these assets are already in place offering individual end-users abundant transport capacity (for example, twisted pair, FttB or coaxial).

Today, having grown to the startling amount of 1.3 billion subscriber identity modules (SIMs) worldwide, borders between 'fixed and mobile' are blurring due to technical developments and end-user needs. Furthermore, emerging unlicensed wireless techniques like wireless local area network (WLAN) do not make it easier for decision makers 'which horse to bet on'.

Figure 3 is complementary to Figure 2. This model is all about ICT marbles that can disappear in and arise from different types of pockets in the ground (where the fixed network part starts). The marbles represent information particles to be moved between end-users and/or information entities (for example, content servers).

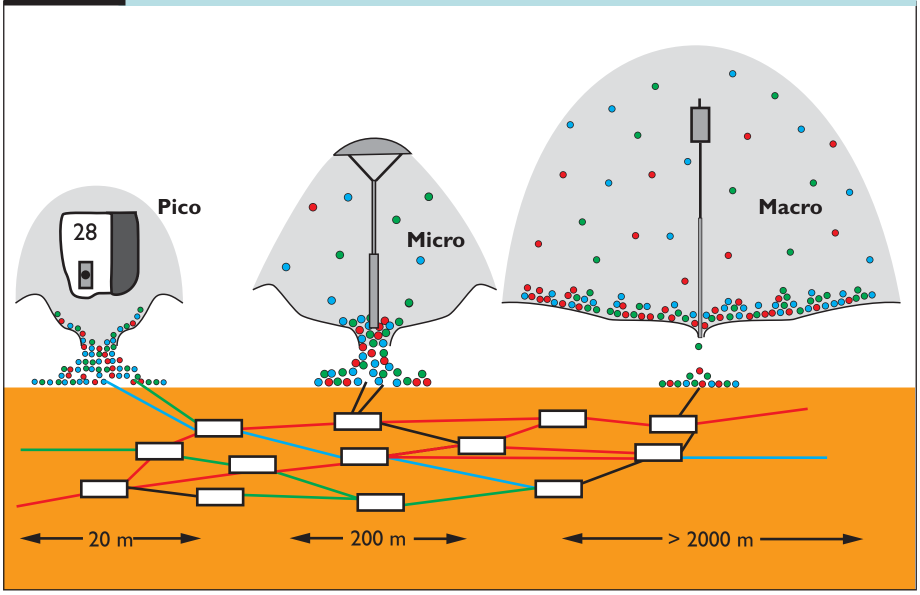
End-users are increasingly free to choose which pockets to use in order to send and receive their marbles. (They are free to choose where and how they want to setup ICT service sessions.) For them it is the game to find the right pocket with the best price-performance ratio customised for each type of marble. Telecom operators/service providers make money on transportation of the particles respecting the agreed service level requirements (such as privacy, transfer time and damage control). Their game is to fill their pockets. Therefore it is crucial from an investment and cost perspective to balance the supply of different pocket types. On both sides of the scale we find:

1. *Macro pockets*: Low-declivity pockets featured by a long radio bearer (large operational radius) offering all capabilities for nomadic use in public space for any subscriber. This type of pocket has a public domain character enabling geographic mobility including seamless roaming and handover functionality.
2. *Pico pockets*: Steep slope pockets featured by a short radio bearer (small operational radius) offering high-bandwidth capabilities. When necessary they can be realised in a private domain setting as well for exclusive use by the end-user (or end-user community). They will certainly not always support all functionality for nomadic use mentioned above.

As described in the introduction, in between these types we find micro pockets. These can for instance be public WLAN hot spots.

As depicted in Figure 3, some lightweight marbles, for example, low-bandwidth conversation marbles, first travel a thousand metres via air to reach the closest centralised (public) macro pocket. For an end-user on the move, this absolutely makes sense. Other heavier marbles, for example, high-bandwidth video content marbles, find their way to a closer (private) pico pocket. The integral cost case (based on distance, bandwidth, QoS, the need for seamless roaming and handover) will determine the geographic balance between air and fixed transport. The future end-user device will sniff and detect the optimal pocket. Given that nearly all services in the future will be 'enjoyed' either wireless or mobile, the radio route to the fixed network can be found in different ways. In this situation, the existence/viability of solitary mobile only and fixed only operators is doubtful.

Figure 3 Marbles and pockets



Technologies and Capabilities per 'Pocket' Type

The three wireless pocket types explained in the previous section correspond to network types usually referred to as wireless *personal area network* (PAN), wireless *local area network* (LAN) and wireless *metropolitan area network* (MAN); to which we also refer as *pico*, *micro* and *macro* pockets or cells, respectively. The coverage radius of wireless PAN is roughly in the order of a few metres up to 20 metres. Wireless LAN coverage radius is limited to about 100 metres, while wireless MAN coverage is in the order of a few kilometres. For each network type, various wireless technologies have been proposed. In this section we limit our scope of attention to the following representative technologies:

- wireless PAN: Bluetooth, UWB;
- wireless LAN: IEEE 802.11a, IEEE 802.11b, IEEE 802.11g; and
- wireless MAN: IEEE 802.16e, GPRS, UMTS.

Table 1 gives an overview of some technical characteristics for each of the above-mentioned technologies. We will not zoom into details of each technology. The characteristic features gathered in Table 1 serve for quality and performance comparison between technologies.

Roaming and handover

No single network technology simultaneously provides low latency, high bandwidth, and wide area data service to a large number of users. The concept of wireless pockets presented in this paper provides a solution by allowing flexible connectivity to a large number of mobile users based on their needs and available resources. In this way, the users can always be connected to the network that serves them best. However, for 'always best connectivity' without

Table 1 Overview of technical characteristics per wireless technology

	Maximum data rate	Frequency allocation	Channel bandwidth	Number of RF Channels	Multiple Access Technology	Typical Range	Mobility Support
Bluetooth	1 Mbit/s	2.4 GHz (ISM)	1 MHz	79	FHSS	10 m	(1)
UWB	110 Mbit/s (at 10 m)	3.1–10.6 GHz	Min. 500 MHz Max. 7.5 GHz	1–15	THSS OFDM (11)	10–15 m	(1)
802.11b	11 Mbit/s	2.4–2.497 GHz (ISM)	25 MHz	3	DSSS	50–80 m (9)	(2)
802.11g	54 Mbit/s	2.4–2.497 GHz (ISM)	(10)	(10)	(10)	50-80 m (9)	(2)
802.11a	54 Mbit/s	various bands in 5 GHz region	20 MHz	US: 12 EU: 8 Japan: 4	OFDM	40-60 m (9)	(2)
802.16e	75 Mbit/s	2–11 GHz 10-66 GHz (3)	1.5–20 MHz (3)	(3)	(15)	30 km (4) 4 km (5)	(6)
GPRS	171 kbit/s (12)	800, 900 and 1800 MHz bands (13)	200 kHz (13)	(13)	TDMA with FDD	1–5 km(14)	Handover possible at high speeds
UMTS (W-CDMA) (8)	2 Mbit/s	1920–1980 MHz 2110–2170 MHz	5 MHz	(7)	DSSS	1–3 km (16)	Handover possible at high speeds

Notes

(1) Technology by itself does not support handover.
(2) Movement within a cell is possible. Technology by itself does not support handover.
(3) IEEE 802.16 is designed for a wide range of licensed and licence-exempt frequencies with flexile bandwidth allocation to accommodate easier cell planning throughout the world.
(4) With 'line of sight' condition.
(5) Without 'line of sight' condition.
(6) Mobility is only supported in the 2–6 GHz band without line of sight. At walking speeds handoff between adjacent cells is possible.
(7) Number of frequency bands depends on the operator's licence.
(8) From different variants of UMTS, we consider here only the European W-CDMA.
(9) Lower bound corresponds to 11 Mbit/s data rate, and upper bound corresponds to 2 Mbit/s data rate.
(10) For data rates 1, 2, 5.5 and 11 Mbit/s the same channel spacing, bandwidth and modulation is used as in IEEE 802.11b (for backwards compatibility). Other supported bit rates use OFDM.
(11) UWB can be implemented using several spreading technologies. Most implementations use OFDM or THSS.
(12) This is the maximum data rate using eight time-slots and Coding Scheme 4 (CS-4).
(13) Same as in GSM.
(14) With Coding Scheme 1 (CS-1), the coverage radius of GSM voice and GPRS data is the same, with CS-2, CS-3 and CS-4 the coverage radius reduces. Typical range in this table is for urban areas. Theoretically the maximum range could be as much as 30 km.
(15) IEEE 802.16 physical layer supports three access technologies: 1. Singles Carrier Modulation (CS), 2. OFDM in combination with TDMA and 3. OFDMA. OFDM and OFDMA are mainly proposed for none 'line of sight' operation.
(16) Typical range in this table is for urban areas. Theoretically the maximum range could be as much as 20 km.

Acronyms

DSSS Direct sequence spread spectrum
FDD Frequency division duplex
FHSS Frequency hopping spread spectrum
GPRS General packet radio service
ISM Industrial, scientific and medical (ISM) frequency bands
OFDM Orthogonal frequency division multiplexing
OFDMA Orthogonal frequency division multiple access
TDMA Time division multiple access
THSS Time hopped spread spectrum
UMTS Universal Mobile Telecommunications System
UWB Ultra-wideband
W-CDMA Wideband code division multiple access
Wi-Fi The 802.11 family is referred to as *Wi-Fi*
WiMAX The 802.16 family is referred to as *WiMAX*

service interruption, it is required to handover a mobile user between network types and radio cells.

In general, handover is applied when a user moves through the coverage area of various cells in a wireless network and crosses cell boundaries. The handover between wireless cells of the same type is often referred to as *horizontal handover*, and the handover between wireless cells of different network types is called *vertical handover*[2]. Roaming can be considered as a special case of handover that requires traffic handling agreements between operators and network providers across country borders.

The wireless cellular networks such as GSM/GPRS and UMTS provide dedicated horizontal handover and roaming solutions within their own network type. However, these solutions are not applicable in a heterogeneous network environment as described in the previous section. Further, networks that are being optimised for the support of wireless broadband data services tend to be based on the IP protocol suit entirely. Since IP was not designed with mobility in mind, several problems need to be solved before 'all-IP' wireless networks could be deployed. The basic problem to be addressed is that, inside an IP network, an IP address is used to identify both a node† and its location. Thus, when a mobile node moves inside the network, its IP address must change. The mobile IP (with two flavours Mobile IPv4 and Mobile IPv6*) is a well-known approach for mobility support in 'all-IP' networks and an accepted standard by the IETF community. This offers a pure network layer architectural solution for mobility support and isolates the higher layer from the impact of mobility. However, an inter-domain mobile IP solution for handover can take up to a few seconds to complete. This is certainly an adequate solution for nomadic users, but, for fast and frequent handover of delay-sensitive voice and multimedia applications, better solutions are required. For this purpose, various adjustments and enhancements to mobile IP have been proposed. Examples are hierarchical mobile IP, cellular IP (CIP) and handoff-aware wireless access Internet infrastructure (Hawaii) for local handover control[4]. However, none of these proposals has been implemented and proved to work on a large-scale basis yet.

† A node is any device connected to a computer network. Nodes can be computers, personal digital assistants (PDA's), cell phones, or various other network appliances. On an IP network, a node is any device with an IP address.

* Mobile IPv6 shares many features with Mobile IPv4, but is integrated into IPv6 and offers some improvements with respect to Mobile IPv4. For an overview see Reference 3.

Comparison of technologies

Looking at Table 1 and considering the handover possibilities and limitations of different technologies we may draw a few rough conclusions:

- Among the mentioned technologies, UMTS and GPRS networks are deployed in the most planned and controlled way. Consequently, interference and capacity estimation are more reliable than other network types. This, in our opinion, is an advantage from the QoS point of view.
- It is evident that wireless PAN, wireless LAN and IEEE802.16e technologies are capable of offering high-bit-rate data services to nomadic users. However, as long as handover and authentication, authorisation and accounting (AAA) problems with these technologies are not solved, UMTS remains the most reliable technology with relatively high-bit-rate support for at least fast-moving users.
- Even though wireless LANs support much higher channel bandwidth than 3G networks, their network-layer handoff latency is still too high to be usable for interactive multimedia applications such as voice over IP or video streaming.
- Because of widespread exploitation and standardisation, and partially due to utilisation of licence-exempt frequency bands, Wi-Fi and WiMAX technologies are financially attractive solutions.

From these observations, it is clear that each of the technologies mentioned here has some advantages and some disadvantages. In the wireless pockets scenario described in Chapters 1 and 2, we do not believe in replacement of one technology by another technology. The strength of any fixed and mobile integrated solution should lie in its capability to combine the strength of all these technologies.

The Role of Gateways

Until today not only do different ICT technology generations coexist, but also technologies have their specific functional position, role, strengths and weaknesses in both the vertically layered hierarchy and the global multi-domain landscape hosting all ICT end-users. Future expectations show a similar image: a heterogeneous composition in which never one single technology will dominate and where not one worldwide monopolistic domain will connect all end-users and (their) active and passive devices. Considering these facts, it is obvious that there will always be a role for gateway functionality:

- interconnecting telecom operator domains (marking the borders between legal entities),
- interconnecting the public Internet and telecom operators (offering fixed, wireless or mobile network access to millions of end-users),
- converting packet- and circuit-based information,
- translating network control information between different signalling systems and domains, and
- connecting public telecom operator domains and private domains (residential gateways being an obligatory building block for an in-house network). Personal network gateways (PNG) can eventually be foreseen.

Since different (access) technologies will coexist (see for example Figure 2) and mobile, fixed and converged telecom operators earn most of their money from offering carrier-grade services, the question is raised who will pay for future gateway functionality, enabling various end-to-end service levels. And even more generally: who is going to timely provision new costly network technology with shorter life cycles at high business risk?

Short-term focus, fierce competition, uncertainties concerning regulation, growing complexity and, above all, strict profit and loss targets, will in practice not be beneficial to the realisation of the required technology mentioned above. It has become a multi-player *trans-sectoral* investment riddle to be jointly solved.

Personal Networks

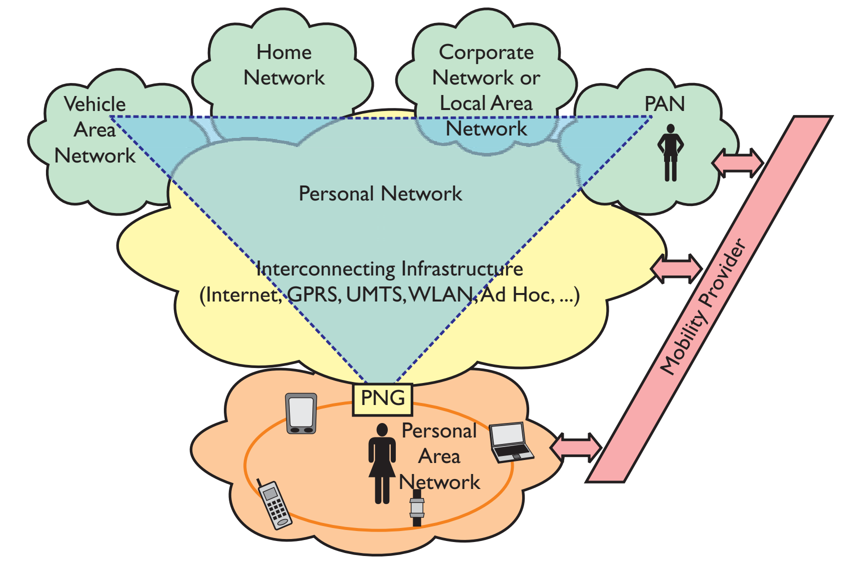
In a converged fixed-mobile architecture as described above, it becomes possible to deploy new kinds of services, such as personal networking, a concept which has been introduced only recently[5, 6]. A personal network is a distributed personal environment consisting of clusters of geographically dispersed devices that dynamically changes according to the context and needs of the user. It is a personalised overlay over multiple domains that hides the underlying network and business complexity from the user. It offers the user access to his/her personal applications, devices and content wherever he/she is, and wherever the devices are and the content is stored, depending on the role of the user (employee, private person, member of a community, etc.) and his/her location, and grants authorisation on the basis of something the user possesses, knows or is.

A schematic view of a personal network is given in Figure 4. At the heart of the personal network is the core PAN, which is physically associated with the owner of the personal network. The core PAN consists of networked personal devices carried by the user (mobile phone, PDA, watch, digital camera, MP3 players, gaming consoles, etc.). Depending on the user location, the core PAN can interact with devices in its environment or with remote devices to temporarily create a personal network. A key element of the core PAN is the personal network gateway (PNG), which is a new category of mobile devices. The PNG is a personal device, possibly with a large amount of local storage and local intelligence, which can connect to multiple wireless (mobile) access networks. The PNG can be a dedicated device, or added functionality of other devices in the core PAN.

Another important enabling factor for the incorporation of the PAN into a fully functional personal network will be the mobility provider (MP). The MP is not a device or a specific application, but a new business role. It is basically a service provider offering the PN service and providing an operational environment to manage user-, service-, content- and network-related issues. For that purpose, the mobility provider uses a service platform like that described in Reference 7, that communicates with the PNG and offers service control functions that enable end-users to easily gain and maintain access to services, while roaming between different access networks. For other service providers it acts as a one-stop shop for providing their services to the personal network and it hides the changes of access networks and terminals due to roaming.

In terms of the four-tiered hierarchy and the 'marbles and pockets' metaphor, a personal network can be envisaged as follows. The PNG is the personal device that receives a command from the core PAN to send or request content (a marble) to or from another device anywhere in the world. It then sniffs for the optimal pocket, by first sensing the environment for available networks, and then communicating with the mobility provider to negotiate about costs, QoS, bandwidth, agility and mobility. Finally, the PNG sends or receives the desired content via the connection of choice, be it fixed, mobile, hot spot or pico cell. In Figure 4, the pockets are basically represented by the yellow and green clouds, and thus can also include other PANs. The mobility provider takes care of the billing and roaming, depending on the subscriptions with the various network and service providers, and on the authentication of the

Figure 4 Personal network



A personal network (blue) is a personalised overlay over multiple domains and interacts with multiple devices. The mobility provider offers the PN service. The PNG connects the core PAN (orange) to the rest of the PN.

devices and content as belonging to the personal network.

The wireless network will always be the limiting factor in offering the required range, bandwidth, and quality of service. The personal network though has enough intelligence to 'find the quickest way to the fixed network'. This fits in perfectly with the view on convergence of fixed and mobile networks as presented in this paper. Up to now, the envisioned broadband services to be supported by fixed networks were limited to 'triple play' (TV, Internet, telephony) and peer-to-peer services. Personal networking adds to that all the services that are perceived as mobile services, but can never be enabled and supported by isolated mobile networks. For consumers it means that they are offered optimal quality and optimal mobility, without the need of explicit choosing between fixed and mobile operators.

Conclusions

In this paper we have provided a future-oriented picture of fixed mobile convergence. Although in the telecommunication community there is general consensus that this convergence is just a matter of time, the ideas for the best convergence scenario are diverse. The proposed idea in this paper is based on the 'marbles and pockets' metaphor that clearly distinguishes one fixed infrastructure layer and three wireless layers, each layer with its own set of technologies and capabilities. The metaphor shows that higher demand for mobility will increase the need for a densely distributed high-capacity fixed access network. Further, as mentioned above, it shows the high potential of the relatively new concept of personal networking in-line with the ongoing trend of personalisation in ICT where the residential gateway tends to be stretched to the human body.

In our convergence scheme, we propose to combine the strength of the described relevant technologies in order to provide the end-user with always-best connectivity. However, we realise that our scenarios could only be feasible if the end-user could be offered the same level of service quality while moving across the layers. In this aspect, it is important to realise the role of the gateways. Finally, for seamless handover between layers, better solutions than the current proposed handover schemes based on mobile IP are required.

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Acknowledgement

The contribution of TU Delft to this paper is supported by the Towards Freeband Communication Impulse of the technology programme of the Ministry of Economic Affairs in The Netherlands.

Biographies

Nico Baken
KPN

Professor Baken currently holds a part-time chair in the Telecommunications Department at Delft University of Technology alongside his primary position as Chief Architect for The Royal KPN, the Dutch incumbent operator in the Netherlands. His main interest concerns broadband networks and services, dealing with a broad range of aspects such as fibre access infrastructures, fixed-mobile convergence, services, operations, financial strategies such as real option analysis, managerial complexity and regulations. Given this spectrum, he has been asked to advice the Dutch government on the matter of broadband and the roll out of fibre to the home in the national expert group broadband and in the Andriessen committee (former minister of Economic Affairs) to deal with the FTTH for Amsterdam and the Hague.

He finished Gymnasium β in 1973 and graduated, cum laude, in mathematics at Eindhoven University of Technology in 1981. He has published over 30 papers, holds several patents and won several prizes for his scientific work; for example, the Dr Neher Laboratory prize (yearly prize for the most outstanding researcher). He received his Ph.D. Thesis from the Delft University of Technology at the department of Electrical Engineering, working with Professor H. Blok and Professor A. T. de Hoop.

Edgar van Boven
KPN

Edgar van Boven studied electronics and IT at the Technical Highschool in Vlissingen. Though tempted to start an adventurous life as a jazz pianist, he graduated in 1987. After military service as a sergeant in a telecommunications battalion, he entered KPN. Until today public telephony has dominated his career from various viewpoints starting with hardware and software engineering, via operational network planning to architecture and programme management. In the late-1990s, he started to work on the evolution to voice over packet in the former Unisource Business Networks environment within KPN. Since 2001, he has also been guest lecturer at the Delft Technical University. Today he is working in the area of fixed mobile convergence.

Frank den Hartog
TNO Telecom

Frank den Hartog received an M.Sc. degree in Applied Physics from the Technische Universiteit Eindhoven in 1992. He obtained a Ph.D. in Physics and Mathematics at Leiden University in 1998, after which he joined KPN Research (in 2003, KPN Research became part of TNO Telecom). He specialised in home networking and established an expert group dedicated to the subject. Currently he is leading the Dutch industrial ICT research projects 'Residential Gateway Environment' and 'Personal Network Pilot 2008', collaborating with, a.o., Philips Research, KPN, and Delft University of Technology. He is a guest lecturer at several universities and (co-)authored about 50 papers and contributions. He is a member of IEEE.

Ramin Hekmat
TU Delft

Ramin Hekmat received an M.Sc. degree in Electrical Engineering from Delft University of Technology in The Netherlands in 1990. Since then he has worked for several telecommunication companies in The Netherlands and the United States in Research and Development as well as managerial positions. In September 2001, he started his Ph.D. work related to ad-hoc networking at TU Delft. His prime research interest includes multi-user communication systems, wireless communications and peer-to-peer networks.