

1

Fundamentals

1.1 4G NETWORKS AND COMPOSITE RADIO ENVIRONMENT

In the wireless communications community we are witnessing more and more the existence of the *composite radio environment (CRE)* and as a consequence the need for *reconfigurability* concepts based on cognitive, cooperative and opportunistic algorithms.

The CRE assumes that different radio networks can be cooperating components in a heterogeneous wireless access infrastructure, through which network providers can more efficiently achieve the required capacity and quality of service (QoS) levels. Reconfigurability enables terminals and network elements dynamically to select and adapt to the most appropriate radio access technologies for handling conditions encountered in specific service area regions and time zones of the day. Both concepts pose new requirements on the management of wireless systems. Nowadays, a multiplicity of radio access technology (RAT) standards are used in wireless communications. As shown in Figure 1.1, these technologies can be roughly categorized into four sets:

- Cellular networks that include second-generation (2G) mobile systems, such as Global System for Mobile Communications (GSM) [1], and their evolutions, often called 2.5G systems, such as enhanced digital GSM evolution (EDGE), General Packet Radio Service (GPRS) [2] and IS 136 in the US. These systems are based on TDMA technology. Third-generation (3G) mobile networks, known as Universal Mobile Telecommunications Systems (UMTS) (WCDMA and cdma2000) [3] are based on CDMA technology that provides up to 2 Mbit/s. Long-term evolution (LTE) [4–12] of these systems is expected to evolve into a 4G system providing up to 100 Mbit/s on the uplink and up to 1 Gbit/s on the downlink. The solutions will be based on a combination of multicarrier and space–time signal formats. The network architectures include macro, micro and pico cellular networks and home (HAN) and personal area networks (PAN).
- Broadband radio access networks (BRANs) [13] or wireless local area networks (WLANs) [14] which are expected to provide up to 1 Gbit/s in 4G. These technologies are based on OFDMA and space–time coding.
- Digital video broadcasting (DVB) [15] and satellite communications.
- Ad hoc and sensor networks with emerging applications.

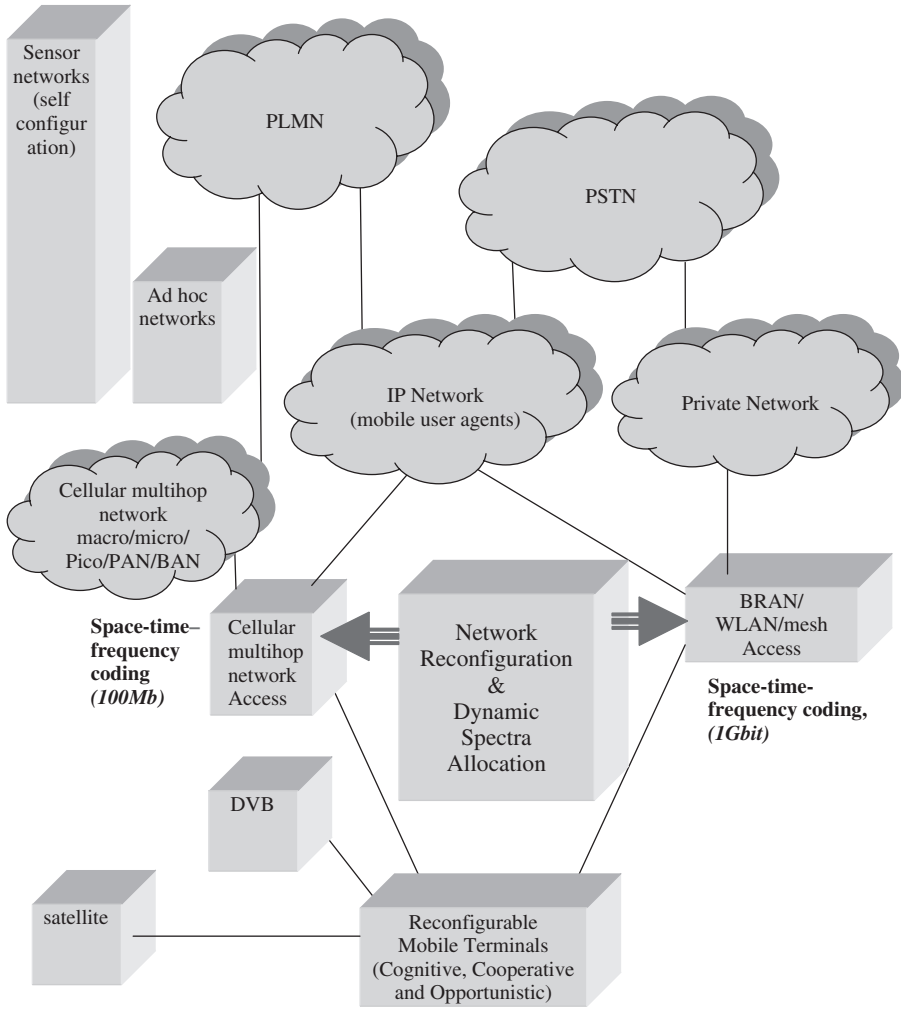


Figure 1.1 Composite radio environment in cognitive, cooperative and opportunistic 4G networks.

In order to increase the spectral efficiency further, besides the space–time frequency coding in the physical layer, the new paradigms like cognitive [16–20], cooperative [21–32] and opportunistic [33–38] solutions will be used.

Although 4G is open for new multiple access schemes, the CRE concept remains attractive for increasing the service provision efficiency and the exploitation possibilities of the available RATs. The main assumption is that the different radio networks, GPRS, UMTS, BRAN/WLAN, DVB and so on, can be components of a heterogeneous wireless access infrastructure. A network provider (NP) can own several components of the CR infrastructure (in other words, can own licenses for deploying and operating different RATs), and can also cooperate with affiliated NPs. In any case, an NP can rely on several alternate radio networks and technologies, for achieving the required capacity and QoS levels, in a cost-efficient manner. Users are directed to the most appropriate radio networks and technologies, at different service area regions and time zones of the day, based on profile requirements and network performance criteria. The various RATs are thus used in a

complementary manner rather than competing each other. Even nowadays a mobile handset can make a handoff between different RATs. The deployment of CRE systems can be facilitated by the *reconfigurability* concept, which is an evolution of a software-defined radio [39, 40]. The CRE requires terminals that are able to work with different RATs, and the existence of multiple radio networks offering alternate wireless access capabilities to service area regions. Reconfigurability supports the CRE concept by providing essential technologies that enable terminals and network elements dynamically (transparently and securely) to select and adapt to the set of RATs that are most appropriate for the conditions encountered in specific service area regions and time zones of the day. According to the reconfigurability concept, RAT selection is not restricted to those that are pre-installed in the network element. In fact, the required software components can be dynamically downloaded, installed and validated. This makes it different from the static paradigm regarding the capabilities of terminals and network elements.

The networks provide wireless access to IP (Internet protocols)-based applications and service continuity in the light of intrasystem mobility. Integration of the network segments in the CR infrastructure is achieved through the management system for the CRE (MS-CRE) component attached to each network. The management system in each network manages a specific radio technology; however, the platforms can cooperate. The fixed (core and backbone) network will consist of public and private segments based on IPv4- and IPv6-based infrastructures. A mobile IP (MIP) will enable the maintenance of IP-level connectivity regardless of the likely changes in the underlying radio technologies used that will be imposed by the CRE concept.

Figures 1.2 and 1.3 depict the architecture of a terminal that is capable of operating in a CRE context. The terminals include software and hardware components (layer 1 and 2 functionalities) for operating with different systems. The higher protocol layers, in accordance with their peer entities in the network, support continuous access to IP-based applications. Different protocol boosters can further enhance the efficiency of the protocol stack. There is a need to provide the best possible IP performance over wireless links, including legacy systems. Within the performance implications of link characteristics (PILC) of the IETF group, the concept of a performance-enhancing proxy

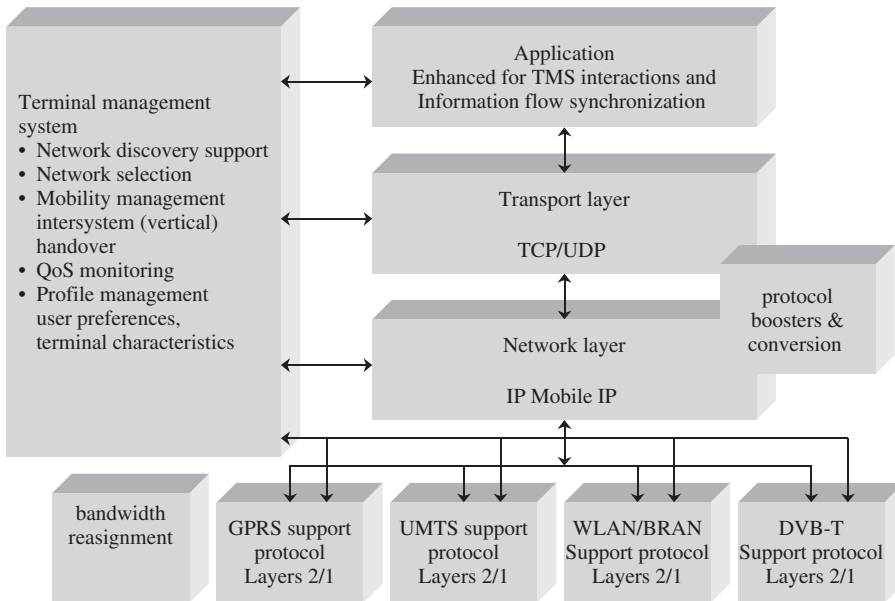


Figure 1.2 Architecture of a terminal that operates in a composite radio environment.

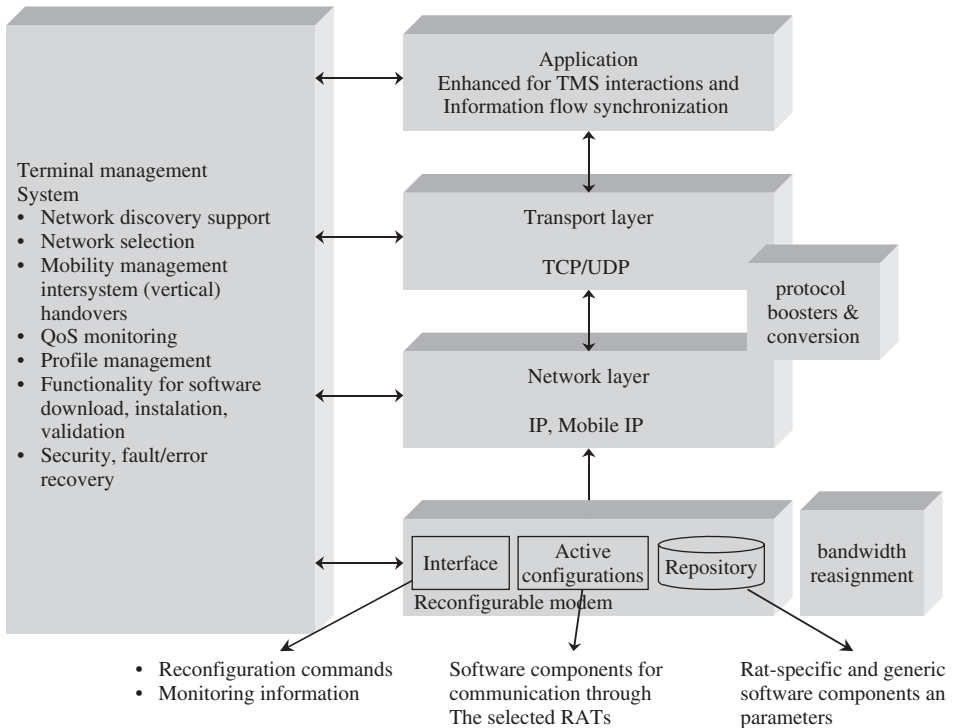


Figure 1.3 Architecture of a terminal that operates in the reconfigurability context.

(PEP) [41–44] has been chosen to refer to a set of methods used to improve the performance of Internet protocols on network paths where native TCP/IP performance is degraded due to characteristics of a link. Different types of PEPs, depending on their basic functioning, are also distinguished. Some of them try to compensate for the poor performance by modifying the protocols themselves. In contrast, a symmetric/asymmetric boosting approach, transparent to the upper layers, is often both more efficient and flexible.

A common framework to house a number of different protocol boosters provides high flexibility, as it may adapt to both the characteristics of the traffic being delivered and the particular conditions of the links. In this sense, a control plane for easing the required information sharing (cross-layer communication and configurability) is needed. Furthermore, another requirement comes from the appearance of multihop communications, as PEPs have been traditionally used over the last hop, so they should be adapted to the multihop scenario.

Most communications networks are subject to time and regional variations in traffic demands, which lead to variations in the degree to which the spectrum is utilized. Therefore, a service's radio spectrum can be underused at certain times or geographical areas, while another service may experience a shortage at the same time/place. Given the high economic value placed on the radio spectrum and the importance of spectrum efficiency, it is clear that wastage of radio spectrum must be avoided. These issues provide the motivation for a scheme called dynamic spectrum allocation (DSA), which aims to manage the spectrum utilized by a converged radio system and share it between participating radio networks over space and time to increase overall spectrum efficiency, as shown in Figures 1.4 and 1.5.

Composite radio systems and reconfigurability, discussed above, are potential enablers of DSA systems. Composite radio systems allow seamless delivery of services through the most appropriate

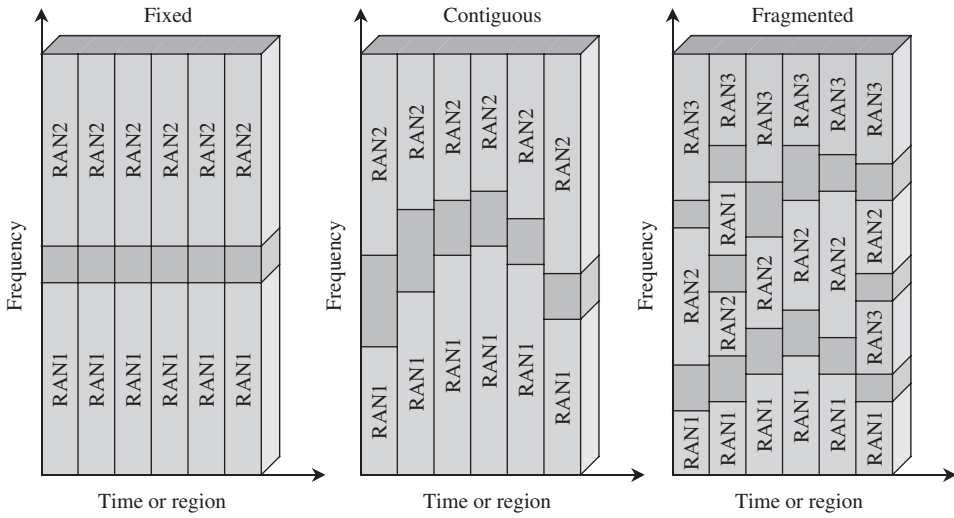


Figure 1.4 Fixed spectrum allocation compared to contiguous and fragmented DSA.

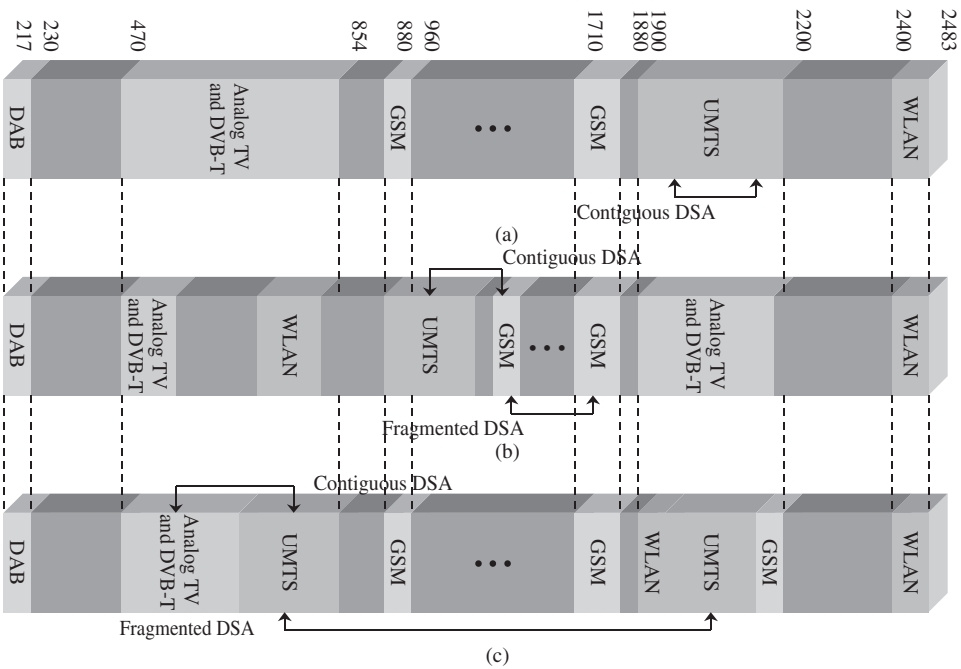


Figure 1.5 DSA operation configurations: (a) static (current spectrum allocations); (b) continuous DSA operations; (c) discrete DSA operations.

access network, and close network cooperation can facilitate the sharing not only of services but also of spectrum. Reconfigurability is also a very important issue, since with a DSA system a radio access network could potentially be allocated any frequency at any time in any location. It should be noted that the application layer is enhanced with the means to synchronize various information streams of the same application, which could be transported simultaneously over different RATs.

The terminal management system (TMS) is essential for providing functionality that exploits the CR environment. On the user/terminal side, the main focus is on the determination of the networks that provide, in a cost-efficient manner, the best QoS levels for the set of active applications. A first requirement is that the MS-CRE should exploit the capabilities of the CR infrastructure. This can be done in a reactive or proactive manner.

Reactively, the MS-CRE reacts to new service area conditions, such as the unexpected emergence of hot spots. Proactively, the management system can anticipate changes in the demand pattern. Such situations can be alleviated by using alternate components of the CR infrastructure to achieve the required capacity and QoS levels. The second requirement is that the MS-CRE should provide resource brokerage functionality to enable the cooperation of the networks of the CR infrastructure. Finally, parts of the MS-CRE should be capable of directing users to the most appropriate networks of the CR infrastructure, where they will obtain services efficiently in terms of cost and QoS. To achieve the above requirements the MS architecture shown in Figure 1.6 is required.

The architecture consists of three main logical entities:

- Monitoring, service-level information and resource brokerage (MSRB).
- Resource management strategies (RMS).
- Session managers (SMs).

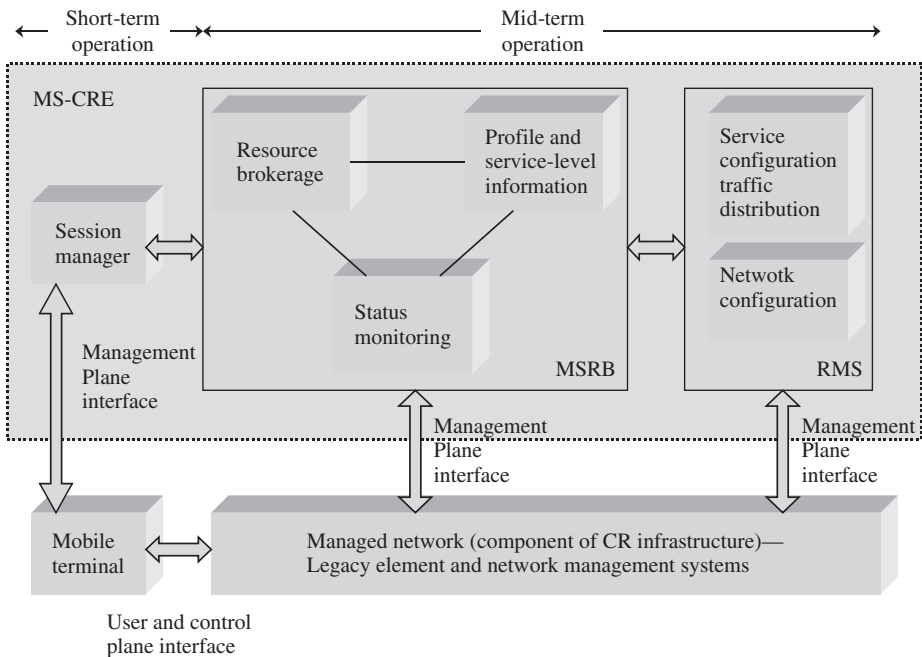


Figure 1.6 Architecture of the MS-CRE.

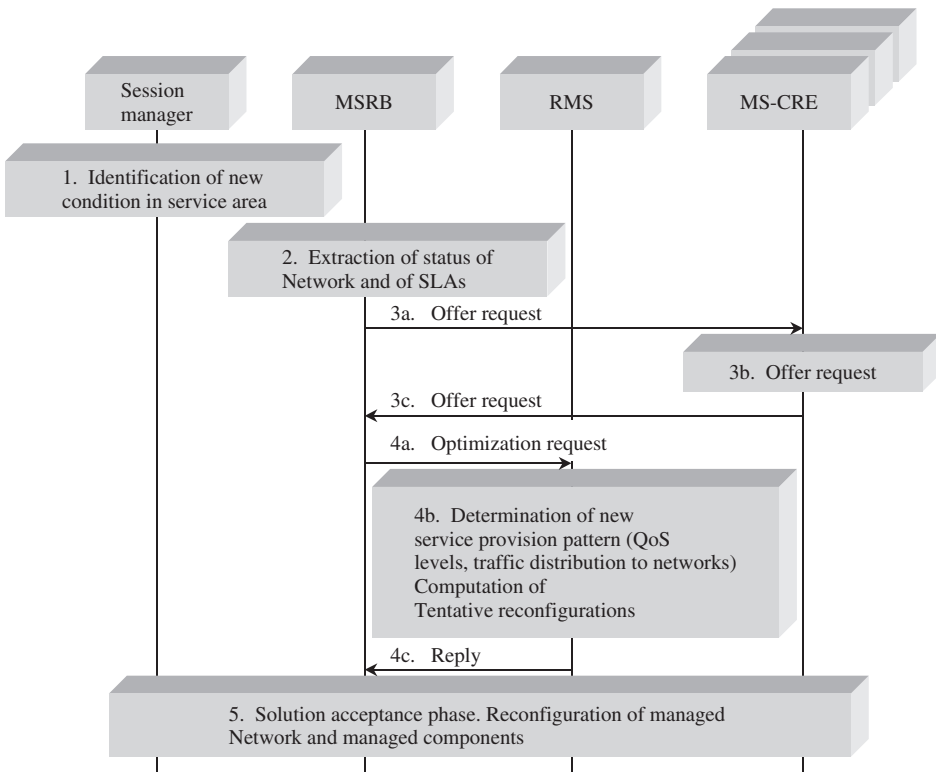


Figure 1.7 MS-CRE operation scenario.

The MSRB entity identifies the triggers (events) that should be handled by the MS-CRE and provides corresponding auxiliary (supporting) functionality. The RMS entity provides the necessary optimization functionality. The SM entity is in charge of interacting with the active subscribed users/terminals. The operation steps and *cooperation of the RMS components* are shown in Figures 1.7 and 1.8, respectively.

In order to gain an insight into the scope and range of possible reconfigurations, we review the network and protocol stack architectures of the basic CRE components as indicated in Figure 1.1.

1.2 PROTOCOL BOOSTERS

As pointed out in Figure 1.2, an element of the reconfiguration in 4G networks are protocol boosters. A protocol booster is a software or hardware module that transparently improves protocol performance. The booster can reside anywhere in the network or end systems, and may operate independently (one-element booster) or in cooperation with other protocol boosters (multielement booster). Protocol boosters provide an architectural alternative to existing protocol adaptation techniques, such as protocol conversion.

A protocol booster is a supporting agent that by itself is not a protocol. It may add, delete or delay protocol messages, but never originates, terminates or converts that protocol. A multielement protocol booster may define new protocol messages to exchange among themselves, but these protocols are originated and terminated by protocol booster elements, and are not visible or

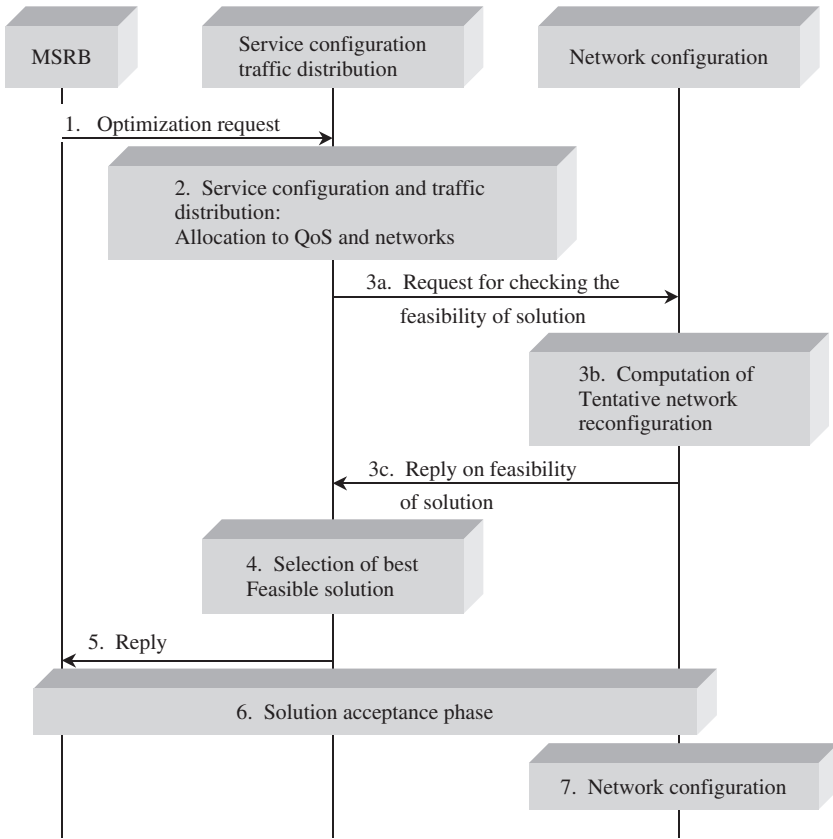


Figure 1.8 Cooperation of the RMS components.

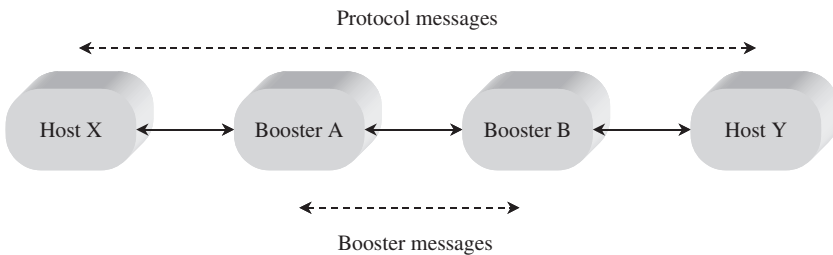


Figure 1.9 Two-element booster.

meaningful external to the booster. Figure 1.9 shows the information flow in a generic two-element booster. A protocol booster is transparent to the protocol being boosted. Thus, the elimination of a protocol booster will not prevent end-to-end communication, as would, for example, the removal of one end of a conversion (e.g. a TCP/IP header compression unit).

In what follows we will present examples of protocol boosters.

1.2.1 One-element error detection booster for UDP

UDP has an optional 16-bit checksum field in the header. If it contains the value zero, it means that the checksum was not computed by the source. Computing this checksum may be wasteful on a reliable LAN. On the other hand, if errors are possible, the checksum greatly improves data integrity. A transmitter sending data does not compute a checksum for either local or remote destinations. For reliable local communication, this saves the checksum computation (at the source and destination). For wide-area communication, the single-element error detection booster computes the checksum and puts it into the UDP header. The booster could be located either in the source host (below the level of UDP) or in a gateway machine.

1.2.2 One-element ACK compression booster for TCP

On a system with asymmetric channel speeds, such as broadcast satellite, the forward (data) channel may be considerably faster than the return (ACK) channel. On such a system, many TCP ACKs may build up in a queue, increasing round-trip time and thus reducing the transmission rate for a given TCP window size. The nature of TCP's cumulative ACKs means that any ACK acknowledges at least as many bytes of data as any earlier ACK. Consequently, if several ACKs are in a queue, it is necessary to keep only the ACK that has arrived most recently. A simple ACK compression booster could ensure that only a single ACK exists in the queue for each TCP connection. (A more sophisticated ACK compression booster allows some duplicate ACKs to pass, allowing the TCP transmitter to get a better picture of network congestion.) The booster increases the protocol performance because it reduces the ACK latency and allows faster transmission for a given window size.

1.2.3 One-element congestion control booster for TCP

Congestion control reduces buffer overflow loss by reducing the transmission rate at the source when the network is congested. A TCP transmitter deduces information about network congestion by examining acknowledgments (ACKs) sent by the TCP receiver. If the transmitter sees several ACKs with the same sequence number, then it assumes that network congestion caused a loss of data messages. If congestion is noted in a subnet, then a congestion control booster could artificially produce duplicate ACKs. The TCP receiver would think that data messages have been lost because of congestion, and would reduce its window size, thus reducing the amount of data it injects into the network.

1.2.4 One-element ARQ booster for TCP

TCP uses ARQ to retransmit data unacknowledged by the receiver when a packet loss is suspected, such as after a retransmission timeout expires. If we assume the network of Figure 1.9 (except that Booster B does not exist), then an ARQ booster for TCP will: (a) cache packets from Host Y; (b) if it sees a duplicate acknowledgment arrive from Host X and it has the next packet in the cache; then it deletes the acknowledgment and retransmits the next packet (because a packet must have been lost between the booster and Host X); and (c) delete packets retransmitted from Host Y that have been acknowledged by Host X. The ARQ booster improves performance by shortening the retransmission path. A typical application would be if Host X were on a wireless network and the booster were on the interface between the wireless and wireline networks.

1.2.5 A forward erasure correction booster for IP or TCP

For many real-time and multicast applications, forward error correction coding is desirable. The two-element FZC booster uses a packet forward error correction code and erasure decoding. The FZC booster at the transmitter side of the network adds parity packets. The FZC booster at the receiver side removes the parity packets and regenerates missing data packets. The FZC booster can be applied between any two points in a network (including the end systems). If applied to an IP, then a sequence number booster adds sequence number information to the data packets before the first FZC booster. If applied to TCP (or any protocol with sequence number information), then the FZC booster can be more efficient because: (1) it does not need to add sequence numbers and (2) it could add new parity information on TCP retransmissions (rather than repeating the same parities). At the receiver side, the FZC booster could combine information from multiple TCP retransmissions for FZC decoding.

1.2.6 Two-element jitter control booster for IP

For real-time communication, we may be interested in bounding the amount of jitter that occurs in the network. A jitter control booster can be used to reduce jitter at the expense of increased latency. At the first booster element, timestamps are generated for each data message that passes. These

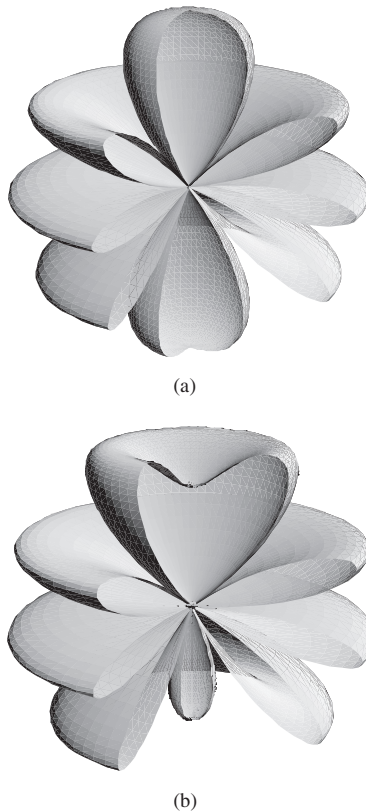


Figure 1.10 Three-dimensional amplitude patterns of a two-element uniform amplitude array for $d = 2\lambda$, directed towards (a) $\theta_0 = 0^\circ$, (b) $\theta_0 = 60^\circ$.

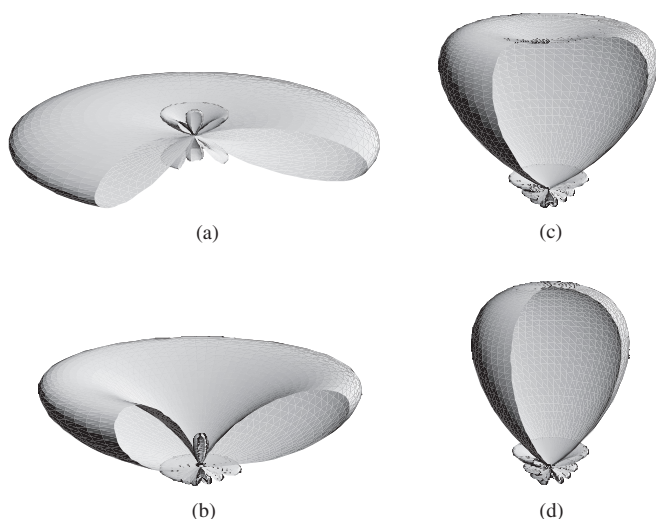


Figure 1.11 Three-dimensional amplitude patterns of a ten-element uniform amplitude array for $d = \lambda/4$, directed towards (a) $\theta_0 = 0^\circ$, (b) $\theta_0 = 30^\circ$, (c) $\theta_0 = 60^\circ$, (d) $\theta_0 = 90^\circ$.

timestamps are transmitted to the second booster element, which delays messages and attempts to reproduce the intermessage interval that was measured by the first booster element.

1.2.7 Two-element selective ARQ booster for IP or TCP

For links with significant error rates using a selective ARQ protocol (with selective acknowledgment and selective retransmission) can significantly improve the efficiency compared to using TCP's ARQ (with cumulative acknowledgment and possibly go-back- N retransmission). The two-element ARQ booster uses a selective ARQ booster to supplement TCP by: (1) caching packets in the upstream booster, (2) sending negative acknowledgments when gaps are detected in the downstream booster and (3) selectively retransmitting the packets requested in the negative acknowledgments (if they are in the cache).

1.3 GREEN WIRELESS NETWORKS

4G wireless networks might be using a spatial notching (angle α) to suppress completely antenna radiation towards the user, as illustrated in Figures 1.10 and 1.11. These solutions will be referred to as 'green wireless networks' for obvious reasons.

In order to ensure the connectivity in the case when the antenna lobe is not directed towards the access point, a multihop communication, with the possibility of relaying, is required. In addition, to reduce the overall transmit power a cooperative transmit diversity, discussed in Section 19.4, and adaptive MAC protocol, discussed in Chapter 5 can be used.

REFERENCES

- [1] M. Mouly and M.-B. Pautet, *The GSM System for Mobile Communications*, Palaiseau, France, 1992.

- [2] R. Kalden, I. Meirick and M. Meyer, Wireless Internet access based on GPRS, *IEEE Pers. Commun.*, vol. 7, no. 2, April 2000, pp. 8–18.
- [3] 3rd Generation Partnership Project (3GPP), <http://www.3gpp.org>.
- [4] P. Mogensen, Wei Na, I. Z. Kovacs, F. Frederiksen, A. Pokhariyal, K. I. Pedersen, T. Kolding, K. Hugl and M. Kuusela, LTE capacity compared to the Shannon bound, in *Vehicular Technology Conf.*, 22–25 April 2007, pp. 1234–1238.
- [5] H. Holma, A. Toskala, K. Ranta-aho, and J. Pirskanen, High-speed packet access evolution in 3GPP Release 7 [Topics in Radio Communications], *IEEE Commun. Mag.*, vol. 45, no. 12, December 2007, pp. 29–35.
- [6] A. Hoikkanen, A techno-economic analysis of 3G long-term evolution for broadband access, in *Conf. on Telecommun. Techno-Economics*, 14–15 June 2007, pp. 1–7.
- [7] A. Racz, A. Temesvary and N. Reider, Handover performance in 3GPP long term evolution (LTE) systems, in *Mobile and Wireless Commun. Summit, 16th IST*, 1–5 July 2007, pp. 1–5.
- [8] M. Valkama, L. Anttila and M. Renfors, Some radio implementation challenges in 3G-LTE context, in *Signal Processing Advances in Wireless Commun., IEEE 8th Workshop on SPAWC 2007*, 17–20 June 2007, pp. 1–5.
- [9] J. J. Sanchez, D. Morales-Jimenez, G. Gomez and J. T. Enrambasaguas, Physical layer performance of long term evolution in cellular technology, in *16th IST Mobile and Wireless Commun. Summit*, 1–5 July 2007, pp. 1–5.
- [10] J. Berkmann, C. Carbonelli, F. Dietrich, C. Drewes and Wen Xu, On 3G LTE terminal implementation – standards, algorithms, complexities and challenges, in *International Wireless Commun. and Mobile Computing Conf., IWCMC '08*, 6–8 August 2008, pp. 970–975.
- [11] C. Spiegel, J. Berkmann, Zijian Bai, T. Scholand and C. Drewes, MIMO schemes in UTRA LTE, a comparison, in *IEEE Vehicular Technology Conf.*, 11–14 May 2008, pp. 2228–2232.
- [12] S.-E. Elayoubi, O. Ben Haddada and B. Fourestie, Performance evaluation of frequency planning schemes in OFDMA-based networks, *IEEE Trans. Wireless Commun.*, vol. 7, no. 5, part 1, May 2008, pp. 1623–1633.
- [13] J. Khun-Jush *et al.*, HiperLAN2: broadband wireless communications at 5 GHz, *IEEE Commun. Mag.*, vol. 40, no. 6, June 2002, pp. 130–137.
- [14] U. Varshney, The status and future of 802.11-based WLANs, *IEEE Comp.*, vol. 36, no. 6, June 2003, pp. 102–105.
- [15] Digital Video Broadcasting (DVB), <http://www.dvb.org>, January 2002.
- [16] V. Stavroulaki, P. Demestichas, A. Katidiotis and D. Petromanolakis, Evolution in equipment management concepts: from reconfigurable to cognitive wireless terminals, in *16th IST Mobile and Wireless Commun. Summit*, 1–5 July 2007, pp. 1–5.
- [17] R. Muraleedharan and L. A. Osadciw, Increasing QoS and security in 4G networks using cognitive intelligence, in *IEEE Globecom Workshops*, 26–30 November 2007, pp. 1–6.
- [18] I. F. Akyildiz, W.-Y. Lee, M. C. Vuran and S. Mohanty, Next generation/dynamic spectrum access/cognitive radio wireless networks: a survey, *Computer Networks J.*, Elsevier, vol. 50, September 2006, pp. 2127–2159.
- [19] M. Muck, D. Bourse, K. Moessner, N. Alonistioti, P. Demestichas, E. Nicollet, E. Buracchini, D. Bateman, Z. Boufidis, E. Patouni, V. Stavroulaki, A. Trogolo and P. Gorla, End-to-end reconfigurability in heterogeneous wireless systems – software and cognitive radio solutions enriched by policy- and context-based decision making, in *16th IST Mobile and Wireless Commun. Summit*, 1–5 July 2007, pp. 1–5.
- [20] B. Aazhang, J. Lilleberg and G. Middleton, Spectrum sharing in a cellular system, in *2004 IEEE Eighth Int. Symp. on Spread Spectrum Techniques and Applications*, 30 August–2 September 2004, pp. 355–359.
- [21] K. Doppler, A. Osseiran, M. Wodeczak and P. Rost, On the integration of cooperative relaying into the WINNER system concept, in *16th IST Mobile and Wireless Commun. Summit*, 1–5 July 2007, pp. 1–5.

- [22] Qian Zhang, Qing Chen, Fan Yang, Xuemin Shen and Zhisheng Niu, Cooperative and opportunistic transmission for wireless ad hoc networks, *IEEE Network*, vol. 21, no. 1, January–February 2007, pp. 14–20.
- [23] M. Katz and F. H. P. Fitzek, Cooperative techniques and principles enabling future 4G wireless networks, in *EUROCON 2005, The Int. Conf. on Computer as a Tool*, vol. 1, 2005, pp. 21–24.
- [24] H. Paloheimo, J. Manner, J. Nieminen and A. Yla-Jaaski, Challenges in packet scheduling in 4G wireless networks, in *2006 IEEE 17th Int. Symp. on Personal, Indoor and Mobile Radio Commun.*, September 2006, pp. 1–6.
- [25] Carlos Leonel Flores Mayorga., Francescantonio della Rosa, Satya Ardhy Wardana, Gianluca Simone., Marie Claire Naima Raynal, Joao Figueiras and Simone Frattasi, Cooperative positioning techniques for mobile localization in 4G cellular networks, in *IEEE Int. Conf. on Pervasive Services*, 15–20 July 2007, pp. 39–44.
- [26] D. Niyato and E. Hossain, A cooperative game framework for bandwidth allocation in 4G heterogeneous wireless networks, in *2006 IEEE Int. Conf. on Commun.*, vol. 9, June 2006, pp. 4357–4362.
- [27] M. Dohler, D.-E. Meddour, S.-M. Senouci and A. Saadani, Cooperation in 4G – hype or ripe?, in *IEEE Technology and Society Mag.*, vol. 27, no. 1, Spring 2008, pp. 13–17.
- [28] S. Frattasi, M. Monti and R. Prasad, A cooperative localization scheme for 4G wireless communications, in *2006 IEEE Radio and Wireless Symp.*, 17–19 January 2006, pp. 287–290.
- [29] C. Politis, T. Oda, S. Dixit, A. Schieder, H.-Y. Lach, M. I. Smirnov, S. Uskela and R. Tafazolli, Cooperative networks for the future wireless world, *IEEE Commun. Mag.*, vol. 42, no. 9, September 2004, pp. 70–79.
- [30] V. Marques, R. L. Aguiar, C. Garcia, J. I. Moreno, C. Beaujean, E. Melin and M. Liebsch, An IP-based QoS architecture for 4G operator scenarios, *IEEE Wireless Commun.* [see also *IEEE Pers. Commun.*], vol. 10, no. 3, June 2003, pp. 54–62.
- [31] Luan Huang, Kar Ann Chew and R. Tafazolli, Network selection for one-to-many services in 3G-broadcasting cooperative networks, in *2005 IEEE 61st Vehicular Technology Conf.*, vol. 5, 30 May–1 June 2005, pp. 2999–3003.
- [32] S. M. S. Masajedian and H. Khoshbin, Cooperative location management method in next generation cellular networks, in *Ninth Int. Symp. on Computers and Communications, ISCC 2004*, vol. 1, 28 June–1 July 2004, pp. 525–530.
- [33] S. Sorrentino and U. Spagnolini, A predictive opportunistic scheduler for 4G wireless systems, in *16th IST Mobile and Wireless Commun. Summit*, 1–5 July 2007, pp. 1–5.
- [34] A. K. F. Khattab and K. M. F. Elsayed, Opportunistic scheduling of delay sensitive traffic in OFDMA-based wireless networks, in *Int. Symp. on a World of Wireless, Mobile and Multimedia Networks, WoWMoM 2006*, 26–29 June 2006, 10 pp.
- [35] Yu Wu, Ji-bo Wei, Yong Xi, Byung-Seo Kim and Sung Won Kim, Opportunistic scheduling with statistical fairness guarantee in wireless networks, in *IEEE 18th Int. Symp. on Personal, Indoor and Mobile Radio Commun., PIMRC 2007*, 3–7 September 2007, pp. 1–5.
- [36] S. Mangold, Zhun Zhong, K. Challapali and Chun-Ting Chou, Spectrum agile radio: radio resource measurements for opportunistic spectrum usage, in *IEEE Global Telecommun. Conf. 2004, GLOBECOM '04*, vol. 6, 29 November–3 December 2004, pp. 3467–3471.
- [37] S. Sanayei, A. Nosratinia and N. Aldhahir, Opportunistic dynamic subchannel allocation in multiuser OFDM networks with limited feedback, in *IEEE Information Theory Workshop, 2004*, 24–29 October 2004, pp. 182–186.
- [38] W. Ajib and D. Haccoun, An overview of scheduling algorithms in MIMO-based fourth-generation wireless systems, *IEEE Network*, vol. 19, no. 5, September–October 2005, pp. 43–48.
- [39] S. Glisic, *Advanced Wireless Communications: 4G Cognitive and Cooperative Broadband Technology*, 2nd edition. John Wiley & Sons, Ltd: Chichester, London, 2007.

- [40] J. Mitola III and G. Maguire Jr, Cognitive radio: making software radios more personal, *IEEE Pers. Commun.*, vol. 6, no. 4, August 1999, pp. 13–18.
- [41] J. Border *et al.*, Performance enhancing proxies intended to mitigate link-related degradations, RFC 3135, June 2001.
- [42] D. C. Feldmeier *et al.*, Protocol boosters, *IEEE J. Selected Areas Commun.*, vol. 16, no. 3, April 1998, pp. 437–444.
- [43] M. García *et al.*, An experimental study of snoop TCP performance over the IEEE 802.11b WLAN, in *5th Int. Symp. on Wireless Personal Multimedia Commun.*, vol. III, Honolulu, HA, October 2002, pp. 1068–1072.
- [44] L. Muñoz *et al.*, Optimizing Internet flows over IEEE 802.11b wireless local area networks: a performance enhancing proxy based on forward error correction, *IEEE Commun. Mag.*, vol. 39, no. 12, December 2001, pp. 60–67.