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Concluding Remarks

Dipankar Raychaudhuri and Mario Gerla

In the previous chapters of this book, we have covered a broad range of networking requirements for emerging wireless scenarios along with the protocol features needed to support them. Clearly, not all of these requirements will be reflected in the general purpose architecture of the Internet, but it may be expected that many of the core capabilities will gradually migrate into mainstream networking protocols that will be in use ten to twenty years into the future. In this concluding chapter, we provide a brief discussion of the roadmap for network evolution or revolution in response to the changes in usage and technology that have been identified in this book.

Although it is impossible to predict exactly how the future Internet of the year 2025 will be realized, we can still enumerate a few alternative scenarios by which the Internet might evolve to meet the many challenges of cellular convergence and mobility. These are:

(1) *Incremental evolution of IP features*: This scenario assumes that the IP standardization process (e.g., IETF and ITU) will anticipate a reasonable set of future requirements and incorporate them into next-generation standards. This would be similar in spirit to IPv6, which improved on IPv4 by providing key features for addressing, mobility, and security. As discussed in Chapter 2, standards processes are already responding to emerging wireless technologies (such as IP-based cellular networks) and usage scenarios (such as multihop wireless access). However, evolution of a widely deployed protocol like IP is quite complicated in its own right, because the degree of design freedom is severely limited by backward compatibility requirements. Also, as new requirements and standards subcommittees are added, it becomes more and more difficult to manage complexity of the resulting protocol standard. Nevertheless, this gradual evolution scenario is perhaps

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the most likely outcome given the inertia of changing any large system as big as the Internet.

(2) *Special-purpose wireless access networks with Internet backhaul*: The second evolution scenario is based on the belief that the core Internet protocol will remain relatively stable and will continue to be used for backbone connectivity. In this concept, the special requirements of wireless access networks for cellular, vehicular, ad hoc, mesh, sensor, and the like will require a specialized access network with its own unique protocol features. This scenario has the disadvantage of requiring protocol gateways between networks, making it difficult for an Internet host across the network to access the features of the wireless access network. This is how cellular networks are currently integrated with the Internet, but there are serious concerns about scalability and the lack of a seamless protocol framework.

(3) *Overlay network architectures for mobility services*: An alternative to the preceding scenario with special-purpose wireless access networks connecting to the general-purpose Internet is to create multiple customized "overlay networks" for different mobility services such as content delivery or video broadcasting. The concept of an overlay network is to deploy routers with new protocols and features on top of IP tunnels used strictly for link-layer connectivity. Overlay networks have proven to be a very flexible strategy for deployment of new networking capabilities while continuing to utilize prior investments in IP as the foundation. The main drawback of overlay networks is the fact that they lack the universality of a single Internet protocol and thus tend to have niche application developer communities. The second problem with overlays is that packets must be processed by two sets of networking protocols, thus increasing latency and processing workload at routers handling large amounts of traffic.

(4) *New clean-slate Internet protocol for emerging mobility services*: In this approach, anticipated requirements for wireless/mobile systems will be integrated into a single clean-slate protocol. Clearly, this is a complex design problem due to the relatively large number of requirements for dealing with user/device mobility, wireless link properties, geographic location, context, and so on. Any new design would have to be validated extensively on large-scale testbeds such as those discussed in Chapter 10, and would subsequently need to be released for more general use with real end-users and applications. The initial bootstrapping of such a new network service is a major challenge, though the availability of programmable networks with virtualized routers and wireless access points will gradually make it easier to try out new protocols at scale. The clean-slate scenario is considered relatively impractical because of the difficulty of competing with the large worldwide base of IP networks, but there are certainly examples of new protocols being

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adopted in a short period – IP and the Web are themselves good examples of this.

(5) *Multiprotocol pluralistic architecture based on network virtualization*: Rather than attempting to combine qualitatively different requirements into a single protocol, it is possible to use network virtualization technology as a foundation capable of supporting a set of otherwise incompatible protocols that have been individually optimized for very different transport services. This so-called *pluralistic network architecture*, which first gained attention in context of experimental networks such as PlanetLab and GENI (see Chapter 10), uses network virtualization and programmability to accommodate multiple independent protocols within the same physical infrastructure. End-user devices attaching to the network will use one or more of the available services by opting in to one or more of the virtual networks. Such a pluralistic architecture also offers the important features of legacy support and graceful migration because existing protocols such as IPv4 can be supported on one of the virtual networks, while speculative new services can be added in parallel by appropriately provisioning additional network slices.

At the time of writing of this book, a number of future Internet research and prototyping activities have been initiated in the United States, Japan, South Korea, and Europe. These activities include the Future Internet Design (FIND) and Global Environment for Network Innovation (GENI) programs started under the auspices of the U.S. National Science Foundation (NSF). The FIND program in particular has supported a large number of clean-slate protocol research ideas during the first phase (2006–2009). These projects span a wide range of topics including network security, economic incentives, content delivery, network virtualization, and the mobile/wireless scenarios considered in this book. The European Union's FP7 program has similar coverage of various future Internet research topics, and includes several projects with a particular focus on mobility aspects. The Japanese future Internet research program (called the "new generation network project") is also a significant activity with coverage of enabling core technologies as well as new protocol architectures.

The NSF FIND program in the United States is currently moving to a second phase (called the Future Internet Architecture [FIA] initiative) aimed at converging early-stage protocol ideas into a small number of competing Internet architectures to be validated and deployed at large scale. It is still too early to assess the impact of these future Internet research initiatives, but it may be expected that the results from these programs will gradually influence the Internet mainstream in terms of design requirements and new protocol components. There is also a slim but nontrivial probability that one or more of the new architectures under evaluation will gain growing acceptance first in research trials and later in real-world deployments. Regardless of the eventual outcome, the journey from today's network to the future Internet with ubiquitous mobility will be an interesting one and will result in many technology and service innovations.