TOWARD SEAMLESS INTERNETWORKING OF
WIRELESS LAN AND CELLULAR NETWORKS

ISSUES IN INTEGRATING CELLULAR NETWORKS, WLANS, AND MANETS: A FUTURISTIC HETEROGENEOUS WIRELESS NETWORK

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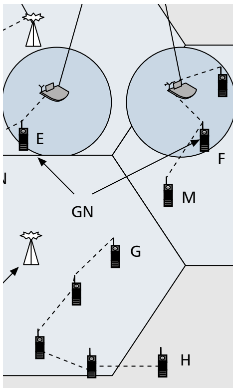

The integration of different technologies with different capabilities and functionalities is an extremely complex task and involves issues at all the layers of the protocol stack. The authors envision an architecture for state-of-the-art heterogeneous multi-hop networks.

ABSTRACT

The popularity of wireless communication systems can be seen almost everywhere in the form of cellular networks, WLANs, and WPANs. In addition, small portable devices have been increasingly equipped with multiple communication interfaces building a heterogeneous environment in terms of access technologies. The desired ubiquitous computing environment of the future has to exploit this multitude of connectivity alternatives resulting from diverse wireless communication systems and different access technologies to provide useful services with guaranteed quality to users. Many new applications require a ubiquitous computing environment capable of accessing information from different portable devices at any time and everywhere. This has motivated researchers to integrate various wireless platforms such as cellular networks, WLANs, and MANETs. Integration of different technologies with different capabilities and functionalities is an extremely complex task and involves issues at all layers of the protocol stack. This article envisions an architecture for state-of-the-art heterogeneous multihop networks, and identifies research issues that need to be addressed for successful integration of heterogeneous technologies for the next generation of wireless and mobile networks.

INTRODUCTION

Recent advances in wireless communications have expanded possible applications from simple voice services in early cellular networks (first and second generation, 1G and 2G) to new integrated data applications. Wireless LANs (WLANs) based on the IEEE 802.11 family have recently become popular for allowing high data rates at relatively low cost. WLAN access points (APs) may provide hotspot connectivity in the most common places, such as airports, hotels, shopping malls, schools, university campuses, and homes. It is expected that future advances in software-defined radio (SDR) and possibly cognitive radio technologies will make multi-interface, environment-aware, multimode, and multiband communication devices commonplace. Such an integrated heterogeneous environment enables a user to access a particular network depending on application needs and types of radio access networks (RANs) available (e.g., cellular network, WLAN, wireless personal area network [WPAN]). For example, in a scenario where a user starts downloading a large video file using the cellular interface of a multimode phone, as higher-data-rate and lower-cost connection through the home IEEE 802.11b AP becomes available, the connection could be automatically switched from the cellular network to the home AP. It is not unrealistic to expect automatic connection and seamless network migration for a single call.

The first step in providing effective and efficient data services is to integrate WLANs (e.g., IEEE 802.11a/b/g and HiperLAN/2), wireless WANs (e.g., 1G, 2G, 2.5G, 3G, the proposed IEEE 802.20), WPANs (e.g., Bluetooth, 802.15.1/3/4), and wireless MANs (e.g., IEEE 802.16) by observing a common characteristic of one-hop (single-hop or infrastructure) operation mode, wherein users access the system through a fixed base station (BS) or AP connected to a wired infrastructure. The second step is to extend this to a multihop communication environment using the revolutionary paradigm of a mobile ad hoc network (MANET), which consists of wireless devices that serve as routers. In a MANET, the router connectivity may change frequently, leading to the multihop communication paradigm that can allow communication without the use of BS/AP, and provide alternative connections inside hotspot cells. Although devices in a MANET often communicate through the WLAN/WPAN interfaces, the mul-

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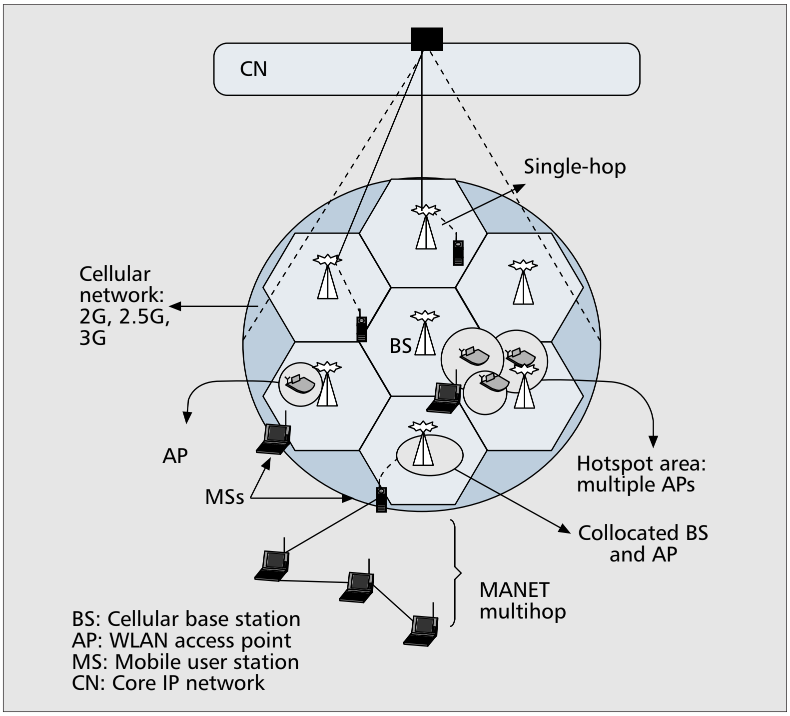
tihop operation mode has several associated issues that are not considered in the single-hop operation mode. Hence, MANETs and WLANs/WPANs operating in single-hop mode need to be differentiated in the design of integrating solutions.

The Third Generation Partnership Project (3GPP) has been developing an interworking architecture for 3G cellular systems and WLANs with the aim of enhancing the services provided to subscribers by 3G operators. An overview of the proposed architecture is given in [1], and the basic interworking aspects considered are network selection, authentication, authorization, and accounting (AAA), and routing in the fixed infrastructure connecting the APs and the 3G network. Although some basic components have been identified, several issues are still under discussion in 3GPP at the time of this writing, mainly regarding the interfaces connecting APs and 3G network components. The 3GPP2 group is also working on 3G/WLAN interworking, but it mostly addresses WLAN/cdma2000 interoperation [2]. One important aspect regarding the standardization work in development at 3GPP and 3GPP2 is the fact that they only consider the integration of WLAN APs with cellular networks; they do not consider WLANs operating in MANET mode as part of the architecture, and consequently do not address issues related to multihop routing.

Therefore, it is necessary to investigate a global heterogeneous architecture and services that together provide seamless integration of single-hop networks (e.g., cellular, WLAN, WWAN) and multihop wireless systems (MANETs). Furthermore, when all these technologies are integrated with the Internet, the possibilities are countless. This is not trivial, however. In this heterogeneous environment, users would have profiles such as price, data rate, battery life, service grade, and mobility pattern. A RAN has to be selected for providing wireless connections, and this should be done based on the user profile and network state (e.g., available bandwidth, congestion status). If a node is not directly within the coverage area of a RAN, we have to assert the possibility of reaching a RAN through multihop communication. Here, the node has to figure out what other nodes in its network can serve as gateways and provide access to RANs.

In this article we discuss the features that would enable us to integrate heterogeneous wireless networks, with more emphasis given to cellular networks, WLANs, and MANETs comprising multi-interface devices. The remainder of this article is organized as follows. We describe a generic integrated network model to identify the critical components and connectivity alternatives in a heterogeneous scenario. We discuss the open research issues in each layer of the protocol stack and the existing architectures for integrating cellular networks, WLANs, and MANETs. We give particular emphasis to the network layer issues, since it is intended to provide a common base and hide the heterogeneity from the upper layers. A comparison of integrated architectures is presented, and finally, concluding remarks are given.



■ **Figure 1**. *Heterogeneous network architecture.*

INGREDIENTS OF A HETEROGENEOUS ARCHITECTURE

A heterogeneous communication network provides transparent and self-configurable WLAN (e.g., IEEE 802.11a/b/g and HiperLAN/2) and wireless WAN (e.g., 1G, 2G, 2.5G, 3G, GSM, the proposed IEEE 802.20) services. The basic components are mobile stations (MSs), BSs/APs, and a core (IP) network (CN), with BSs and APs serving as the communication bridges for MSs (Fig. 1). WLANs can operate in infrastructure (single-hop) mode, where connectivity is provided by an AP, or in MANET mode, where devices can communicate with each other through multihop routing. These two operation modes have different characteristics and particular issues that need to be addressed separately in an integrated architecture. In the hotspot area, multiple APs may overlap to some extent; also, a BS and an AP may be collocated. MSs can arbitrarily move, and at a given instant a particular MS can either be within or outside the coverage of BSs and/or APs. A connection from an MS to a BS/AP can be established by a single hop or using multihop when the MS is out of the coverage of the corresponding BS/AP, as shown in Fig. 1. Factors influencing the design of such a heterogeneous architecture include multi-interface MSs, transmission power and co-channel interference, topology and routing, mobility and handoff, load balance, interoperability, and quality of service (QoS) provisioning.

MOBILE USER STATIONS

Despite a plethora of technology alternatives and future wireless interfaces, we can identify the following basic MS types: single-mode cellular, single-mode WLAN, and dual-mode. A single-mode cellular MS connects to a cellular network through a BS. A single-mode WLAN can communicate through an AP or connect to other WLAN equipped terminals in ad hoc mode, forming a MANET. A dual-mode MS can operate in both the infrastructure (communicating directly to a BS or AP) and MANET modes using the WLAN interface. For example, in the UCAN architecture [3] each MS uses two air interfaces: a high-data-rate (HDR) interface for communicating with a BS and an IEEE 802.11 interface for peer-to-peer communication. More and more MSs will be equipped with multiple interfaces based on different wireless medium access technologies (e.g., HDR interface, IEEE 802.11, IEEE 802.16, and Bluetooth), so user requirements could be supported with better connectivity.

BASE STATION AND ACCESS POINT

The integration of cellular networks, WLANs, and MANETs is not straightforward due to various communication scenarios, different interface capabilities, and mobility patterns of MSs. Fixed network components, such as BSs and APs, can provide several services to MSs, including:

- Access to the Internet
- Interoperability of existing networks and future networks
- Support of handoff between different wireless access networks
- Resources control
- Routing discovery
- Security management

Both BSs and APs should have the capability of interoperability with each other, and also the possibility of integration with new emerging networks for supporting handoffs between them. APs and BSs also have the responsibility to manage and control radio resources for the MSs. In fact, frequency allocation becomes more complicated since different wireless technologies may possibly operate in the same frequency band, which makes coexistence mechanisms increasingly important. The high processing and power capacity of APs and BSs make them strategic components in selecting optimum routes between two MSs. Furthermore, the APs and BSs can implement load balance functionalities by switching connections from infrastructure mode to MANET mode, or diverting connections to a free neighboring BS or AP by multihop communication.

CORE IP NETWORK

The CN serves as the backbone network with Internet connectivity and packet data services, but also supports seamless mobility, multihop cooperation, and security. The nodes in the CN may support Mobile IP and Cellular IP to provide continuous connectivity for MSs when they move between cellular networks and WLANs, or change their points of attachment on cellular networks or WLANs. An integrated billing scheme and possibly a reward mechanism are required in the CN to encourage packet forwarding for multihop communication. Another important issue is security, and the CN plays an important role in preventing several types of attacks by supporting authentication for all types of MSs.

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POSSIBLE COMMUNICATION SCENARIOS

In the heterogeneous environment shown in Fig. 1, different types of connections can be established between any two MSs. For example, consider two MSs, SRC and DST, that try to establish a connection. The MS SRC (DST) can be under the coverage of an AP (cellular network). Another possibility is when both are using a WLAN interface, but DST is operating in MANET mode, while SRC is connected to an AP. When SRC and DST are both single-mode cellular terminals, the only possibility is to use the cellular network. The most general case is when both end systems SRC and DST have dual-mode capability. In this case, 10 different connection scenarios are possible. The following scenarios can be seen in Fig. 2, assuming that all MSs have dual-mode capability:

1) SRC = A and DST = B can communicate through the cellular interface, and the connection setup follows the typical procedure of the cellular network.

2) SRC = C and DST = D can be connected through one WLAN AP in infrastructure mode.

3) SRC = E and DST = F can communicate to their APs, and these APs are interconnected through a fixed network.

4) SRC = G and DST = H can use the WLAN interface in MANET mode to communicate directly or through multiple hops.

5) SRC = I can use the WLAN interface in the MANET mode to connect to a gateway node (GN = S), which can establish a connection to DST = A through a cellular BS in infrastructure mode.

6) SRC = J can use its WLAN interface in MANET mode to connect to GN = C), which can establish a connection to DST = D through a WLAN AP in infrastructure mode.

7) Both SRC = K and DST = L are out of the coverage of an AP, but they can connect using multihop ad hoc mode by identifying the corresponding GN = C and GN = D, which can communicate through the AP.

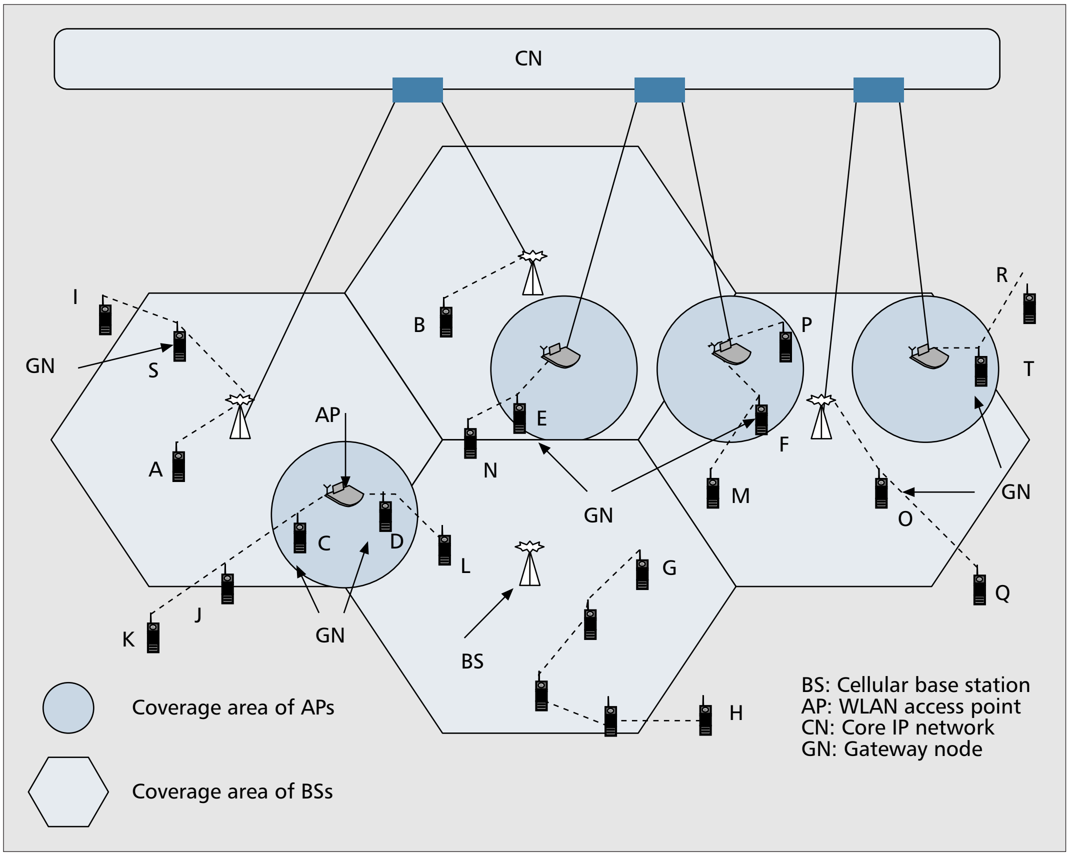
8) Both SRC = M and DST = N are out of the coverage of APs, but they can connect using multihop ad hoc mode by identifying corresponding GN = F and GN = E, whicht can communicate through the fixed infrastructure (CN) in the infrastructure mode.

9) SRC = O and DST = P are using the cellular and WLAN interfaces, respectively, and the corresponding BS and AP are connected through the fixed CN.

10) SRC = Q is using its WLAN interface to connect to a GN (O) that is connected to the BS, and this BS is connected through the CN to the AP that provides connectivity to the destination terminal DST = R through GN = T.

DESIGN FACTORS

There are three unique features significantly affecting the design of integrated solutions, namely, the availability of multiple interfaces for an MS, the integration of cellular networks and WLANs, and multihop communication. Several questions need to be addressed in order to provide an integrated, transparent, and self-configurable service. A fundamental question is what



■ **Figure 2**. *Connection alternatives between two dual-mode MSs.*

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technology (or communication interface) to select to initiate a connection for a particular application? Another question is when to switch an ongoing connection from one interface to another (vertical handoff)? Other important issues include transmission power selection for a given communication interface, co-channel interference, topology discovery, route creation, mobility and handoff management, and load balancing. Some of these questions have been addressed by researchers in several integration architectures. However, none of the existing models incorporate all these design factors. Clearly, the answers will depend on the MS's capabilities, connectivity options available at the current location, the user's mobility profile, the QoS expected, and the service cost. For instance, the decision of which interface to use should be automatically made by the system; the selection of the end-to-end route for a particular connection may be based on the user's service level agreement (SLA). Besides the goal of satisfying the user requirements, the selection of a given technology or the decision to perform a vertical handoff can also be used to enhance the overall system performance or to implement the functionality of load balance.

THE PROTOCOL STACK

In a homogeneous network, all network entities run the same protocol stack, where each layer has a particular goal and provides services to the upper layers. In a heterogeneous environment as shown in Fig. 1, different mobile devices can execute different protocols for a given layer. The protocol stack of a dual-mode MS is given in Fig. 3. This protocol stack consists of multiple physical, data link, and medium access control (MAC) layers, and network, transport, and application layers. Therefore, it is critical to select the most appropriate combination of lower layers (link, MAC, and physical) that could provide the best service to the upper layers. Furthermore, some control planes such as mobility management and connection management can be added. These control planes can eventually use information from several layers to implement their functionalities. As shown in Fig. 3, the network layer has a fundamental role in this process, since it is the interface between available communications interfaces (or access technologies) that operate in a point-to-point fashion, and the end-to-end (transport and application) layers. In other words, the task of the network layer is to provide a uniform substrate over which transport (e.g., TCP and UDP) and application protocols can efficiently run, independent of the access technologies used in each of the point-to-point links in an end-to-end connection. Although there are issues in all layers, the network layer has received more attention than any other layer, and little integration related work has been done at the lower layers. Indeed, integrated architectures are expected not to require modifications at the lower layers so that different wireless technologies can operate independently [1]. However, this integration task is extremely complex, and it requires the support of integration architecture in terms of mobility and connection manage-

In a heterogeneous environment, different wireless technologies may be operating in the same frequency band, and it is critical that they must coexist without degrading the performance of each other. Therefore, interference mitigation techniques are important.

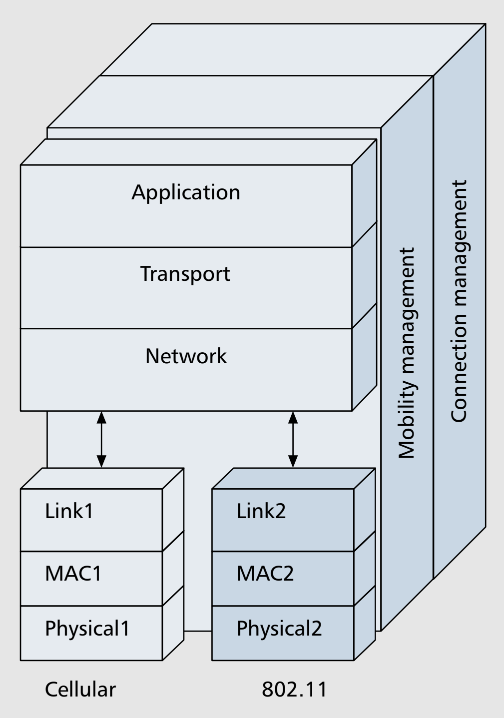

Figure 3. *The protocol stack of a dual-mode MS in a heterogeneous network environment.*

ment. Seamless handoffs for "out of coverage" terminals and resource management can be provided by the two control planes shown in Fig. 3.

THE PHYSICAL LAYER

MSs equipped with multiple network interfaces may be able to access multiple networks simultaneously. Even though SDR-based MSs are not fully capable of simultaneously accessing multiple wireless systems, discovering the access networks available for a given connection must be performed. If an MS is connected to a cellular network, and it is also within the coverage area of an 802.11b AP, the network or the MS needs to be able to switch between them.

In a heterogeneous environment, different wireless technologies may be operating in the same frequency band, and it is critical that they coexist without degrading the performance of each other. Therefore, interference mitigation techniques are important. For MSs far away from their APs, for example, multihop communication links may result in less interference than direct transmission to the AP, while multihop links between MSs closer to the AP may considerably decrease its capacity due to interference. Power control techniques have been applied to limit interference in code-division multiple access (CDMA)-based cellular networks and MANETs, and coexistence of IEEE 802.11 WLAN and Bluetooth has been analyzed [4].

Open Research Issues — The open research issues range from SDR-based terminal design to power control techniques and can be summarized as follows:

- Efficient design of SDR-based MSs that can efficiently switch between different technologies and provide higher data rates
- Frequency planning schemes for BSs/APs that could satisfy users' requirements while increasing the spectrum utilization
- Interference mitigation techniques between various wireless access technologies

Note that modulation techniques and coding schemes that improve the performance of a given technology will always be among the physical layer design challenges.

THE DATA LINK LAYER

The data link layer can be divided into logical link control (link) and MAC layers. The MSs will be able to use a centralized MAC, such as time-division multiple access (TDMA) or CDMA, when connecting to a cellular network, or a distributed random access scheme, such as carrier sense multiple access with collision avoidance (CSMA/CA), in an IEEE 802.11 WLAN. These access methods can provide different service levels in terms of capacity and delay. The data rate in the cellular interface can reach up to 2.4 Mb/s (the maximum in the current cdma2000/HDR standard), while an 802.11b interface can provide up to 11 Mb/s. The achievable throughput and delay in CSMA/CA highly depends on the traffic load. Problems such as hidden and exposed terminals are known to limit the capacity of IEEE 802.11. Furthermore, when two MSs are communicating through multiple intermediary hops in MANET mode, performance can be even worse due to MAC layer random access problems in each intermediary hop. It is known that the CSMA/CA scheme used in the IEEE 802.11 standard has serious performance limitations when used in a multihop environment. Mechanisms such as power control and power-aware MAC protocols can be used to improve performance.

In a heterogeneous network, an end-to-end connection can involve a sequence of several different links and MAC-layer connections, and the final end-to-end performance will be limited by the "weakest" link in this chain of connections; cross-layer design may play an important role in providing useful information to upper layers. Security is also an important issue to be considered at the link/MAC level. Although end-to-end security is considered in the application layer, some wireless access technologies provide a certain level of security at the lower layers. IEEE 802.11 Task Group I (TGi), for example, has been set to design new security architecture as part of the 802.11i standard.

Open Research Issues — The link and MAC layers in a dual-mode MS can operate independently, but their operations have to be optimized to provide guaranteed service to the upper layers. Some of the open issues at these layers include:

- Design of efficient link and MAC layer protocols for MANETs and WLANs that support different QoS levels
- Channel management schemes in cellular networks that consider different categories of traffic, and result in low call blocking and handoff failure (call dropping) probabilities
- Link/MAC layer security
- Efficient spectrum utilization

THE NETWORK LAYER

The network layer seems to be the most challenging as it integrates all the technologies. The multiple interfaces of MSs can have different physical and MAC layer protocols, which must be taken into account in an integrated routing process. The routing problem also inherits all the issues related to multihop routing in MANETs, such as frequent route changes due to mobility, higher control overhead to discover and maintain valid routes, higher end-to-end delay, and limited end-to-end capacity due to problems at the lower layers (e.g., collisions at the MAC layer and interference at the physical layer). Some existing integrating solutions limit the number of multihops to a maximum of 2 or 3 [3, 5, 6]. However, it is not clear to what extent multihop connections can enhance system performance. Moreover, integrated solutions may rely on high processing and power capabilities of fixed network components (BSs and APs).

The idea of integrating MANETs with infrastructure networks is motivated not only by traffic load reduction in the BSs/APs and improving the overall cell throughput, but also by providing connectivity to MSs out of BS/AP coverage using GNs. Hence, the network layer must have mechanisms to allow these MSs in a MANET to find such gateways and correctly configure their IP addresses. Furthermore, the MSs connected to the fixed infrastructure must be aware of the MSs in the MANET part that can be reached through GNs. In other words, the network layer has to discover the integrated topology and find the best route between any source and destination pair. Several metrics can be used to define the best route, including number of hops, delay, throughput, signal strength, and so on. Depending on the metric used, different paths including different wireless technologies can be selected as the best option. Furthermore, the network layer has to handle horizontal handoffs between BSs/APs of the same technology and vertical handoffs between different technologies in a seamless manner.

Integrated Architectures — Although there is no solution that considers all the possibilities described in Fig. 2, several architectures and hybrid routing protocols have been proposed to integrate single-hop (infrastructure mode) and multihop networks. The architectures and routing protocols discussed in this section include UCAN, two-hop relay, one-hop and two-hop direct transmission, HWN, MCN, iCAR, MADF, A-GSM, ODMA, and SOPRANO. A detailed comparison of these integrated architectures is provided later.

UCAN — The unified cellular and ad hoc networks architecture (UCAN) [3] considers dual-mode MSs with a cellular CDMA/HDR interface and an IEEE 802.11b interface that can operate in MANET mode. The UCAN architecture can be applied in a situation similar to scenario 5 in Fig. 2, with all nodes assumed to be under BS coverage (a unique cell). The basic goal is to use multihop routing to improve the throughput when the quality of the signal in the downlink channel between the BS and the MS is poor. The system uses GNs (called *proxy clients*) with better downlink signal quality to relay packets toward the destination MS in MANET mode. Thus, MSs have to discover the proxy clients that act as the interface between the MANET and the cellular network, as well as decide when to execute vertical handoffs. Two proxy client discovery protocols were proposed in [3], a proactive greedy scheme and an on-demand protocol. MSs monitor pilot bursts sent by the BS to estimate their current downlink channel conditions, and uses this information in the proxy discovery and routing process. Once a client currently receiving data from the BS experiences degradation on the received data rate, it can send a route request (RTREQ) on the 802.11b interface trying to establish a new route (using a proxy client) to receive the data from the BS. The route request propagates through the ad hoc network (with a limited number of hops controlled by a time to live, TTL, field) to find a proxy client.

Two-Hop-Relay — The two-hop relay architecture [5] also exploits the availability of dual-mode terminals that can act as relay gateways (RGs) between the single-hop and multihop domains (as shown in scenarios 5–8, Fig. 2); it considers not only cellular BSs, but also WLAN APs. As suggested in [5], the RGs can be nodes placed by a wireless carrier or dual-mode MSs able to act as RGs. The two main goals in this architecture are to enhance the capacity of an existing cellular network and extend system coverage for WLAN MSs by up to two hops. As in UCAN [3], MSs with low downlink quality of signal from the BS can use multihop connections to achieve higher data rates. The RG can be used by WLAN MSs that are out of the AP's coverage only if they are properly registered with the cellular network. The RG periodically broadcasts relay advertisements through its WLAN interface, including its own identifier (GWid), the current BS/AP identifier (BSid), the bandwidth indicator type (BI-T) for QoS control, the bandwidth indicator value (BI-V), and the registration method (RM). Therefore, before establishing a connection, a dual-mode MS must decide whether to directly transmit to the BS/AP or to send a relay request to an RG after receiving the advertisement message. On its side, the RG stores the identification of the MS, forwards the relay request to the cellular network, and waits for the authentication and authorization response from the cellular network. Finally, when the cellular network sends the relay replay, the RG informs the MS of the status of authorization of the connection.

One- and Two-Hop Direct Transmission — The authors in [6] proposed hybrid protocols for integrating single-hop and multihop operation in a WLAN environment, thereby combining the strengths of the two models to solve problems such as AP failures and handoff procedures in single-hop mode, and weak connection in multihop mode. These protocols can be used in a scenario similar to 8 in Fig. 2. Several control messages are introduced for multihop operation as well as to

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When a node detects that the next hop is unreachable, it sends a route error packet to the BS and buffers the current packet. The BS responds with a route reply to the node that generated the route error and also sends a correct route packet to the source node.

allow MSs to discover GNs (called *agents*) to connect to an AP. If a receiver moves such that it can no longer directly hear the sender's signal but can still receive data from one of the sender's neighbors, the connection can be switched to two-hop-direction transmission mode. However, if no sender's neighbor is accessible from the new receiver's position, they can still use the AP-oriented communication mode.

Hybrid Wireless Network Architecture — The hybrid wireless network (HWN) architecture [7] allows each cell (BS) to select the operation mode between typical single-hop for sparse topologies or MANET mode for dense ones. It is assumed that all MSs have Global Positioning System (GPS) capabilities and periodically send location information to the BS, which in turn runs an algorithm to decide the operation mode that could maximize throughput. In the switching algorithm, the BS estimates and compares the throughput in MANET mode with the current throughput in single-hop mode. If the current operation mode is ad hoc, the BS compares the achieved throughput with $B/2N$, where B is the achievable bandwidth per cell and N is the number of MSs per cell. Furthermore, the BS periodically broadcasts the minimum transmission power required to keep the network connected in MANET mode. The authors have suggested the IEEE 802.11 point coordination function (PCF) as a MAC protocol for cellular mode, and the distributed coordination function (DCF) for MANET mode [7].

Two drawbacks of the HWN architecture are that the minimum power used in the MANET mode can lead to disconnected topologies due to mobility, and ongoing connections could be broken during the switching period. Also, the centralized selection of the mode for all connections may not optimize cell performance, and a better option may be to choose the operation mode on a per connection basis.

Multihop Cellular Network Architecture — In the multihop cellular network (MCN) architecture [8], all cells use the same data and control channels. The MS and BS data transmission power is reduced to half the cell radius to enable multiple simultaneous transmissions using the same channel. It is argued that this reduction factor of two represents a compromise between increasing the spatial reuse and keeping the number of wireless hops to a minimum. The transmission power in the control channel corresponds to the cell radius, and the MSs use this channel to send information about their neighbors to the BS. To ensure reliable connectivity information at the BS, the nodes recognize their neighbors using a contention-free beacon protocol. When an MS wants to connect to a given destination, it sends a route request to the BS on the control channel. Then, using the topology information, the BS finds the shortest path (using Djikstra's algorithm) between the source and destination, and sends back a route reply with the shortest path to the source node. Upon receiving the route reply, the source node inserts the route into the packet and begins its transmission. In addition, the nodes cache route information to eliminate the control overhead. When a node detects that the next hop is unreachable, it sends a route error packet to the BS and buffers the current packet. The BS responds with a route reply to the node that generated the route error and also sends a correct route packet to the source node.

iCAR and MADF — In iCAR [9] the ad hoc relay stations (ARSs) are wireless devices deployed by the network operator and equipped with two interfaces, one to communicate with the cellular BSs and another to communicate in MANET mode with other ARSs (WLAN interface). Furthermore, the ARSs can have limited mobility controlled by the cellular mobile switching center (MSC) in order to adapt to traffic variations. The iCAR architecture uses ARSs to balance the traffic load between cells. ARSs can divert the traffic from an overloaded cell to an uncongested one; that is, although the source and destination MSs can be located in a congested cell, the ARS to a neighboring cell can relay the connection. Besides load balancing, iCAR can also increase the coverage of a cellular network, since MSs out of cellular coverage can access the system through the relay stations.

Like iCAR, mobile-assisted data forwarding (MADF) [10] achieves load balance between cells by forwarding part of the traffic in an overcrowded cell to some free cells. Unlike iCAR, which uses stationary ARSs as relays, traffic forwarding in MADF is achieved using MSs as relaying nodes that are located between overloaded (hot) cells and free (cold) ones. Relaying MSs share a number of forwarding channels and continuously monitor the delay of their packets. If packet delay is high, the MS stops forwarding and requests the BS to forward data packets to another neighboring cold cell. If the hot cell returns to low traffic, the MS may stop its MADF forwarding and redirect packets back to its own cell. If MSs in a hot BS are far away from one another, the same forwarding channels can be reused by two MSs to forward data to different neighboring BSs without interference. The implementation of MADF in an Aloha network and a TDMA network shows that the throughput in a hot cell surrounded by some cold cells can be significantly improved [10]. The primary advantage of MADF over iCAR is that there is no need for additional devices.

A-GSM and ODMA — The ad hoc Global System for Mobile Communications (A-GSM) architecture [11] allows GSM dual-mode MSs to relay packets in MANET mode and provide connectivity in dead spot areas, thereby increasing system capacity and robustness against link failures. The dual-mode MSs in [11] are equipped with a GSM air interface and a MANET interface; when one interface is being used, the other can detect the availability of the alternative connectivity mode. The MSs have an internal unit called a dual-mode identity and internetworking unit (DIMIWU), which is responsible for performing the physical and MAC layer protocol adaptation required for each air interface (i.e., GSM or MANET — A-GSM). At the link layer, A-GSM mode uses an adaptation of the GSM Link

Access Protocol for D channel (LAPDm) that supports the transmission of beacon signals to advertise their capabilities of serving as relay nodes. In the beacon message, a relay node can include the BS to which it can connect, as well as the respective number of hops required to reach the BS. The drawback of this proactive gateway discovery scheme is the high control overhead.

The basic idea in A-GSM is the same as in the opportunity-driven multiple access (ODMA) scheme [11, reference therein]. Both solutions integrate multiple accesses and relaying function to support multihop connections. ODMA breaks a single CDMA transmission from an MS to a BS, or vice versa, into a number of smaller radio hops by using other MSs in the same cell to relay the packets, thereby reducing the transmission power and co-channel interference. However, ODMA does not support communications for MSs outside the coverage of BSs, while A-GSM does.

SOPRANO — The Self-Organizing Packet Radio Ad Hoc Network with Overlay (SOPRANO) [12] investigates some of the techniques by which the capacity of a cellular network can be enhanced, including bandwidth allocation, access control, routing, traffic control, and profile management. The SOPRANO architecture advocates six steps of self-organization for the physical, data link, and network layers to optimize the network capacity: neighbor discovery, connection setup, channel assignment, planning transmit/receive mode, mobility management and topology updating, and exchange of control and router information. Multi-user detection (MUD) is also suggested for the physical layer since MUD is an effective technique to reduce the excessive interference due to multihop relaying. In the MAC layer, if transmissions are directed to a node through several intermediate nodes by multihop, clever frequency channel assignments for each node can significantly reduce interference and could result in better performance. In the network layer, for enhancing system capacity, multihop routing strategy must take into account the traffic, interference, and energy consumption.

Open Research Issues — Although several routing protocols have been proposed for heterogeneous communication networks, the design of integrated and intelligent routing protocols is largely open for research:

- Routing capability in a heterogeneous environment that supports all communication alternatives described in Fig. 2
- Scalability in multihop routing without drastically increasing the overhead
- The impact of additional routing constraints (co-channel interference, load balance, bandwidth, and terminal interfaces), and requirements (services, speed, packet delay) needed by MSs and networks

THE TRANSPORT LAYER

The performance degradation of TCP is the most important issue in any wireless transport layer, as all losses are assumed to be due to congestion, and factors such as channel errors, delay variations, and handoffs are ignored. Several modified versions of TCP have been proposed to handle non-congestion-related losses. In a heterogeneous scenario where MSs are equipped with multiple interfaces and several access networks are available, the transport protocol has to handle the high delays involved in connection switching from one interface to another (vertical handoff procedures), server migration, and bandwidth aggregation [13]. Since a TCP connection is identified by the tuple (IP address, port number) of both endpoints, the basic problem is how to maintain a TCP connection when an MS changes its IP address as it enters a new access network. Network layer solutions, such as Mobile IP, incur relatively high delay. Due to firewalls, server migration support may be required when the MS cannot access the original application server using the new access network address. Also, the overlap of coverage between different access technologies can be exploited to improve the aggregate connection's bandwidth. However, the MS must consider the trade-off between achieved throughput, power consumption, and cost before using multiple active interfaces [13].

The performance degradation of TCP is the most important issue in any wireless transport layer, as all losses are assumed to be due to congestion, and factors such as channel errors, delay variations, and handoffs are ignored.

Most approaches enhance TCP performance in wireless networks by providing the sender with feedback information about the causes of the errors at the wireless links. A receiver-centric approach called Reception Control Protocol (RCP) was proposed in [13], such that the receiver closer to the wireless last hop (where most errors occur) can obtain more accurate information about causes of losses and avoid feedback overhead by taking proper actions. In the case of server migration, the overhead required to transfer connection state information from one server to another is minimized, since the receiver has the control information. An extension of the RCP protocol for hosts with multiple interfaces, called Radial RCP (R2CP), was also proposed in [13] to support seamless handoffs and bandwidth aggregation. R2CP aggregates multiple RCP connections into one abstract connection for the application layer. The protocol keeps multiple states at the host according to the number of active interfaces. Then in a vertical handoff, the application can continue transmitting and receiving data in the old interface before the new connection is established. Note that the advantages of a receiver-centric transport protocol are highlighted when the sender is in a fixed network. When both ends are connected to wireless access networks (e.g., scenario 8, Fig. 2), the errors can occur not only close to the receiver, but also near the last wireless link at the sender side.

Open Research Issues — The main open problems at the transport level are:

- Design a new transport protocol or adapt the existing protocols (mainly TCP) to take delays into account in vertical handoffs for end-to-end congestion control process.
- Implement server migration without interrupting ongoing connections, and support bandwidth aggregation by exploiting the availability of multiple interfaces.

In a heterogeneous environment, the applications should only have access to the transport layer and network services as in the OSI network model, and all the underlying complexity should be hidden.

THE APPLICATION LAYER

In a heterogeneous environment, applications should only have access to the transport layer and network services as in the open systems interconnection (OSI) network model, and all underlying complexity should be hidden. As discussed above, the network layer needs to exploit the availability of multiple access technologies and communication interfaces in the MSs to meet application QoS requirements. The multiple access networks available in a given location can also provide different types of application services to users. For example, WLAN APs placed along the path to an airport can provide flight information service. In this case, WLAN-capable MSs should be able to discover and inform on user availability of such service. In fixed networks, some particular nodes can be selected to store service availability information, while in MANETs decentralized service discovery schemes are required. A basic problem is how to provide information about services available in the fixed network part (through BSs or APs) to MSs participating in a MANET. Therefore, some kind of virtual service manager is needed that can filter relevant information.

Due to multihop routing, the design of charging and/or rewarding schemes in the application layer becomes a critical issue to encourage collaboration in packet forwarding [3]. Another fundamental problem is end-to-end security. In an adversarial environment, the heterogeneous network may suffer from various security threats that may degrade the efficiency of packet relaying, increase packet delivery latency, increase packet loss rate, and so on. Integrated security aspects have been considered in the 3G/WLAN interworking architectures under development in 3GPP [1] and 3GPP2 [2], but a more general and robust framework has to be investigated as MANET operation is also considered.

Open Research Issues — Some of the open issues at the application layer include:
- End-to-end security
- Service discovery mechanisms
- Credit charging and rewarding mechanisms

MOBILITY AND CONNECTION MANAGEMENT

As shown in Fig. 3, mobility and connection management are two control planes that can provide the capability of neighborhood topology discovery, detect available Internet access, as well as support vertical handoffs. In fact, the mobility and connection management functionalities cannot be clearly separated.

In a heterogeneous network, there are two types of handoffs: horizontal (between AP/BS of the same network) and vertical (between different interfaces or access networks). Horizontal handoffs can be handled by the cellular/WLAN network components at the link layer, and at the network layer Mobile IP (Mobile IPv4 and IPv6) can provide an effective solution for macro and global mobility management. However, in a micromobility environment inside the same cellular network, the latency in the handoff process may increase significantly. Several micromobility management schemes have been proposed to reduce handoff latency (e.g., Cellular IP, Hawai, TeleMIP); most of them introduce new Mobile IP agents, and some of them, such as TeleMIP, use Dynamic Host Configuration Protocol (DHCP) servers to discover the new network.

In the case of vertical handoffs, two basic issues have to be considered: when to start the handoff process, and how to redirect the traffic between interfaces. Note that the process of discovering the availability of a given technology also needs to be supported for vertical handoffs. In order to use the functionalities of Mobile IP, the MS needs to register with a home agent running on a fixed Internet gateway (IGW). In cellular networks and WLANs in infrastructure mode, the BSs and APs can be connected to Mobile IP agents acting as IGWs. Several trigger events for vertical handoffs are described in Table 1 [14].

The redirection process can be performed in a seamless or reactive way [14]. The first alternative is possible when the MS is under the coverage of the technologies corresponding to its interfaces and wants to start a vertical handoff to optimize QoS or perform load balance among its interfaces. For instance, an MS currently downloading a file using the cellular interface can redirect the flow to the 802.11 interface if it is also under the coverage of the 802.11 AP. On the other hand, the reactive redirection is triggered by an interface down event (network failure), so the packets can be received at a different interface. Clearly, packets will be lost if the MS starts the redirection process only after detecting that the interface is down. No integrated solution exists to handle all possible types of vertical handoffs in a heterogeneous environment such as that shown in Fig. 2.

The main issue with vertical handoff is latency, which can generally be characterized by three components [15]:
- Detection period is the time taken by the MS to discover an IGW.
- Address configuration interval is the time taken by an MS, after detecting an IGW, to update its routing table and assign its interface a new care-of address (CoA) based on the prefix of the new access network.
- Network registration time is the time taken to send a binding update to the home agent as well as to the correspondent node, and the time it takes to receive the first packet on the new interface.

When the discovery phase is based on IGW advertisements (reactive IGW discovery), some schemes have been proposed to reduce handoff latency in a GPRS/WLAN scenario [15]: fast router advertisements, route advertisements caching, binding update simulcasting, smart buffer management using a proxy in GPRS, and layer 3 soft handover. An extension of Mobile IPv6 is proposed in [14], multiple interface management (MMI), which redirects traffic flows between two interfaces with two corresponding global IPv6 addresses.

Open Research Issues — In summary, some of the open research issues to be considered at the mobility and connection management layers are:

- Efficient gateway discovery protocols to integrate MANETs with fixed network components
- Development of new mobility and connection management approaches to reduce delay during vertical handoffs

COMPARISON OF THE INTEGRATED ARCHITECTURES

In this section we provide a comparison of existing architectures proposed for heterogeneous integrated networks. The first aspect to compare is the scenarios considered by a particular architecture. The A-GSM, ODMA, and iCAR proposals introduce the ad hoc mode (MANET) in a cellular system by exploiting dual-mode terminals' capabilities, but they do not consider the possibility of integrating WLAN APs. On the other hand, the one- and two-hop direct transmission protocols are especially designed to integrate infrastructure and MANET mode in WLANs. The HWN and MCN architectures also focus on the integration of a generic single-hop mode (cellular or WLAN) and MANETs, but do not consider dual-mode terminals. The UCAN and two-hop relay architectures consider the most general scenario, including cellular network and WLAN in cellular-based mode and MANET mode. However, the results with these schemes presented in [3, 5] assume that all nodes are dual-mode and under a single cellular BS coverage, and no WLAN AP is included in the evaluations.

As shown in Table 2, a common goal of the integration schemes is to improve the capacity in the infrastructure-based (BS or AP) systems by allowing some multihop transmissions. In A-GSM and ODMA, the reduction in the MS's transmission power is also identified as an advantage, since MSs far away from the BS do not need to increase their transmission power to reach the BS, but rather can use relatively low power levels to connect to a nearby relay terminal in ad hoc mode that provides a path to the BS.

The ODMA proposal achieves a capacity gain by reducing the interference level inside the cell, as some of the connections are established in MANET mode. iCAR uses multihop only to transfer connections between BSs, performing load balance in the system. Different from the other schemes, the HWN and MCN approaches assume that the cell can operate only in cellular-based or ad hoc mode. By fixing a particular mode for all connections, the overall cell capacity will depend on the current topology. Hence, if the topology changes frequently, there can be higher overhead and performance degradation in frequently switching between operation modes. Since different connections can have different QoS requirements, selecting the transmission mode for each connection request seems to be the most suitable approach. In HWN the routing protocol (BS-controlled or multihop routing) depends on the operation mode, while in MCN the route is selected by the BS even under ad hoc operation mode. In UCAN, the decision of the multihop route between the destination MS and the BS is based on the quality of the downlink transmission rate of the nodes in the path. Indeed, the GN (client proxy) for a given connection has to have a higher downlink rate than the other terminals in the multihop path.

Trigger Event	Description
Interface down	An interface currently used fails, so the MS cannot receive its flows anymore.
Interface up	A new interface is available, e.g., the MS enters the coverage area of a new access network.
Horizontal handoff procedure	As a horizontal handoff in the currently used interface is started, the MS can redirect the traffic to another interface to reduce undesirable effects of the high delay involved in the handoff process.
Change in network capabilities	The QoS provided by one interface improves or degrades (coverage, data rate, power consumption, etc).

Table 1. *Trigger events for vertical handoffs.*

Another important aspect to consider is connectivity support for MSs participating only in MANETs (i.e., out of the coverage of any BS or AP). In an integrated scenario, BSs and APs can also act as IGWs for out-of-coverage MSs, but a gateway discovery process is required. Although the A-GSM scheme does not specifically consider the integration of isolated MANETs with the cellular network, one of its aims is to provide connectivity for terminals in dead spot areas, increasing the coverage of the cellular network. In ODMA, iCAR, UCAN, HWN, and MCN, all nodes are assumed to be under a BS's or an AP's coverage.

Although most architectures use some kind of GN as the interface between infrastructure and MANET modes, the GN's capabilities and responsibilities are not the same in all cases. For instance, GNs can provide connectivity to MSs out of infrastructure coverage, as in A-GSM and two-hop relay, or be used only to improve the performance inside a cell (UCAN) or perform load balancing (iCAR). Hence, in the former case, out-of-coverage MSs have to find a GN in order to join the network, which involves tasks such as registration, authentication, and addressing, while in the latter case the MS uses the GN as the last hop in the multihop path to connect to a BS or an AP, and some performance metrics are used in the gateway selection. Despite the gateways' functionalities, however, the network has to provide some means for the MSs to discover them.

Basically, gateway discovery can be performed in a proactive or reactive fashion, and each approach has its advantages and drawbacks. Proactive schemes generally provide a faster response time at the cost of more control traffic, while reactive discovery can reduce the amount of control traffic, but cannot achieve the same response time. The proactive scheme is used in A-GSM and two-hop relay, where the GNs periodically send advertise messages. In UCAN the MS starts the search for a gateway as needed (reactive approach), but two different discovery protocols were proposed: in a proactive approach the MS keeps track of its neighbors' capabilities to act as a gateway (downlink transmission rate); in a reactive scheme the request for a gateway is forwarded until a candidate gateway is found (i.e., an MS with better downlink rate than the requesting MS). In iCAR, only one-hop transmissions are allowed between a typical MS and a GN (ASR), such that the MS can search for a gateway among its one-hop neighbors. In one- and two-hop direct transmission protocols, the MS can send a specific control message to find a gateway to connect to a nearby AP when its current AP fails. There is no concept of GN in ODMA, HWN, and MCN, as all MSs are assumed to be under cellular system coverage.

The general aim in most cases is to enhance users' throughput and improve overall system performance, but no proposed architecture considers the applications' QoS requirements in selection of transmission mode, routing process, or handoff procedures.

CONCLUDING REMARKS

Future networking ought to integrate a myriad of heterogeneous terminals and access technologies, such as cellular, WLAN, WMAN, and WPAN networks. Accessibility alternatives provide different QoS and coverage levels. The

Architecture	Operation modes considered	Main optimization goal	Types of mobile user stations	Supported scenarios or its variation in Fig. 2	Support of out-of-coverage MSs	Connection mode/ gateway discovery
A-GSM	Cellular — MANET	Coverage, transmission power reduction and capacity	Dual-mode	1, 5	Yes	GNs send beacon (advertise) messages (proactive scheme)
ODMA	Cellular — MANET	Transmission power reduction and BS capacity	Dual-mode	1, 5, but all MSs are under coverage of BSs	No	There is no concept of gateway, every node can relay packets, and the routing decision is based on the signal quality
iCAR	Cellular — MANET	Load balance between BSs	Single-mode and dual-mode	1, 5	No	The GN nodes are deployed in planned positions, and the MS can only use one-hop-away GNs
UCAN	Cellular — WLAN — MANET	BS/AP throughput and user downlink data rate	Single-mode and dual-mode	1–3, 5, but all MSs are under coverage of BSs	No	MSs search for GNs when their transmission rate decreases below a given threshold (proactive or reactive discovery)
Two-hop relay	Cellular — WLAN — MANET	BS/AP throughput	Single-mode and dual-mode	3, 5–8	Yes	The GNs send advertising messages (proactive scheme)
One- and two-hop direct transmission	WLAN — MANET	Reliability to AP failures and handoffs	Single-mode	3, 8	Yes	Destination MS selects the connection mode, but MSs can act as gateways in case of AP failures
HWN	WLAN or Cellular — MANET	BS or AP throughput	Single-mode	(1), (4)	No	BS selects the cell's operation mode
MCN	WLAN or Cellular — MANET	BS or AP throughput	Single-mode	1–4	No	BS/AP selects the operation mode and execute a centralized routing algorithm
MADF	Cellular — MANET	Load balance between BSs	Single-mode	1, 5	No	Ad hoc routing protocol for routing discovery
SOPRANO	Cellular - MANET	BS capacity	Single-mode	1, 5	No	Routing decision is based on minimum interference and energy

Table 2. *Comparison of integrated architectures.*

complexity of such a heterogeneous environment must not only be hidden from end users, but also be made transparent to applications. The task of designing future adaptable heterogeneous networks that provide QoS guarantees to users is extremely complex and challenging. In this article we discuss open research issues that need to be addressed in order to integrate cellular, WLANs, and MANETs. We describe the issues at each layer of the protocol stack as well as various features and limitations of existing integration architectures. The complexity in providing an integrated routing functionality increases with the necessity to consider MSs operating in a MANET. Although the basic goal in several proposed integration architectures is to use multihop routing to enhance performance in cellular-based networks, the possibility of providing connectivity to users out of BS/AP coverage is also required to have a truly pervasive computing environment. Another fundamental task of the network layer is to support seamless horizontal and vertical handoffs to minimize overall delay. Furthermore, service discovery and security mechanisms also need to be provided.

Future networking ought to integrate a myriad of heterogeneous terminals and access technologies. The complexity of such an environment not only needs to be hidden from the end users, but also to be made transparent to the applications.

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