A SURVEY OF CONVERGING SOLUTIONS FOR HETEROGENEOUS MOBILE NETWORKS

MINHO JO, TARAS MAKSYMYUK, RODRIGO L. BATISTA, TARCISIO F. MACIEL, ANDRÉ L.F. DE ALMEIDA, AND MYKHAILO KLYMASH

ABSTRACT

In 5G systems, the current machine-to-machine communications using Wi-Fi or Bluetooth provide a good opportunity to dramatically increase overall performance. Converged mobile networks can provide M2M communications with significant performance improvements by sharing unlicensed spectrum bands in cellular networks, such as Long Term Evolution-Advanced, by using cognitive radio technology. Thus, the converged mobile network will become one of the most popular future research topics because mobile multimedia content services have been generally accepted among mobile device users. In this article, we provide an overview of converged mobile networks, investigating different types of converged mobile networks, different types of convergence, and the current problems and solutions. This survey article also proposes potential research topics in converged mobile networks.

INTRODUCTION

Since the number of mobile multimedia content users has increased dramatically, a serious problem over limited spectrum resources has arisen. In order to solve this problem, research has recently begun investigating increasing available spectrum resources by integrating (or converging) several network resources into a single mobile network. This single converged mobile network allows each different network to share the idle resources of other networks. However, each of these existing types of networks, such as cellular networks, video broadcasting, wireless sensor networks (WSNs), and wireless local area networks (WLANs), works independently using its own frequency band. Currently, there are already many emerging mobile convergence network technologies. Thus, this survey article addresses the problems and solutions of existing mobile convergence networks and discusses their future research topics.

The advent of Long Term Evolution (LTE) technology has allowed the provision of high-throughput applications for mobile users. In addition, the development of hardware such as smartphones/tablets and mobile operating systems (OSs) such as Android, iOS, Windows Phone, and Tizen have accelerated mobile service development, requiring plenty of spectrum bands. Indeed, we have seen an extremely wide range of various mobile applications, web services, and real-time multimedia services these days. Until recently, most of these services were available only for fixed-location users.

A popular topic in the current information and communication technologies area is cloud computing, which is widely recognized as a next-generation computing infrastructure. Cloud services enable users to adaptively utilize resources, and thus allow service providers to easily implement mobile applications with minimal management effort. Mobile cloud computing brings new types of services and allows mobile users to access services previously available only to desktop computer users, including real-time services, interactive games, and ultra-high definition (UHD) video streaming, which requires much higher performance from mobile networks. Even LTE networks are not able to properly support them. Therefore, some new technologies for increasing performance, including fifth-generation (5G) mobile networks, have been proposed over the last few years [1]. Convergence of heterogeneous wireless access techniques has emerged as one of the key solutions for 5G mobile networks. In mobile converged networks, users access many kinds of mobile services, despite their location, connection type, and device.

The converged mobile network allows users to effectively utilize the multiple transmitters/receivers operating in standards such as LTE-Advanced (LTE-A), Wi-Fi, Bluetooth, and ZigBee. For example, users can be reallocated between different types of network (LTE, LAN, Wi-Fi, ZigBee, etc.) without session interruption, or even simultaneously utilize resources from different networks [2].

In this article, we provide an overview of converged (heterogeneous) mobile networks, and then discuss key problems and existing solutions for the coexistence of different wireless protocols, such as cellular, broadcast, Wi-Fi, and Bluetooth networks, within the same spectrum

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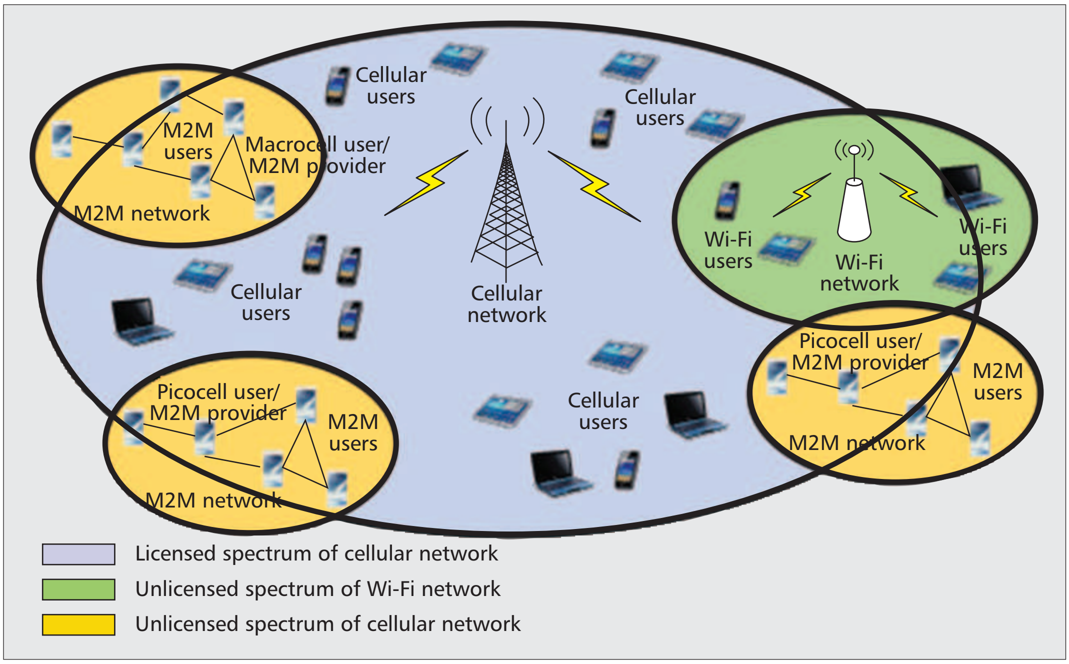

Figure 1. Converged mobile network including LTE-A, Wi-Fi, and M2M networks.

In service convergence, continuous mobile content service is the goal, regardless of device changes and inter-network handover. Full convergence will be one type where the other three types will be integrated. It will be technically very complex, but an interesting future research topic.

band. Utilization of unlicensed spectrum bands in converged mobile networks is addressed by using cognitive radio technology [3].

This article is organized as follows. An overview of mobile converged network development is discussed. We focus on the possible heterogeneous scenarios in mobile converged networks. We cover coexistence solutions and interference avoidance within converged heterogeneous mobile networks. We conclude this article.

Overview of Converged Mobile Network Development

First Model and Most Recent Model of Converged Mobile Networks

When developing the LTE standard, the Third Generation Partnership Project (3GPP) introduced a new improved version known as LTE-A. LTE-A was the first step toward network heterogeneity due to relay transmission possibilities. LTE-A networks were not heterogeneous at first, because they used only a single protocol and shared the same licensed spectrum. However, the latest development allows sharing different unlicensed spectrum bands (Wi-Fi, Bluetooth, etc.) for relay transmission [4], and supports effective handover between LTE-A cellular networks and Wi-Fi or Bluetooth networks. In particular, the convergence of two different network protocols, Wi-Fi and LTE-A, is achieved via connection of fixed Wi-Fi access points with LTE-A core networks through fixed or wireless relay transmission. Mobile Wi-Fi/Bluetooth access point technology was proposed to improve the flexibility of converged mobile networks. This new converged technology will also consider machine-to-machine (M2M) communications sharing the available unlicensed spectrums of Wi-Fi, Bluetooth, and ZigBee. An example of mobile converged networks with different wireless access techniques is shown in Fig. 1.

Three Main Types of Converged Mobile Networks

We see three main types of converged mobile networks: device convergence, protocol convergence, and service convergence. Device convergence was the first step, based on integrating multiple communication interfaces within one device. This type of convergence assumes the simultaneous use of different types of separate communication sessions by one device. As an example, a user is able to use an LTE-A network for voice communication, simultaneously transferring data from a smartphone to a laptop via Bluetooth. However, in this convergence, each separate communication session is controlled by the user. The second type of mobile network is protocol convergence. In the second type, different network protocols (LTE, Wi-Fi, Bluetooth, etc.) are used within a single heterogeneous network. As an example of this scenario, we consider an LTE-A network with Wi-Fi access points, which supports soft handover between cellular and Wi-Fi networks controlled by the provider. In service convergence, continuous mobile content service is the goal, regardless of device changes and internetwork handover. Full convergence will be one type where the other three types are integrated. It will be technically very complex, but an interesting future research topic. The different convergence types and their features are summarized in Table 1.

Future Research Topics in Converged Mobile Networks

Full mobile network convergence will be a promising future research topic model because it is technically very complex but eventually pro-

Type of convergence	Objectives	Subjects	Features	Stage of development
Device convergence (Type 1)	Integration of different communication interfaces within single end-use devices	Users' devices and their interfaces	Simultaneous holding of separate user-controlled communication sessions by a single device	Completely achieved
Protocol convergence (Type 2)	Convergence of different communication protocols within one logical network	Communication protocols	Soft handover between different communication protocols without session interruption	Almost completely achieved
Service convergence (Type 3)	Convergence of network services under one heterogeneous mobile network	Network services and users' devices	Continuous service maintained regardless of user device and connection type	Partially achieved
Full convergence (Future)	Full convergence of any user's devices, communication protocols and network services	Network services and users' infrastructures	Independence from users' devices, communication networks, and service providers	None

Table 1. Comparison of four different types of convergence.

vides total quality of service (QoS) to users. In order to achieve full convergence in mobile networks, a lot of technical problems must be solved. A wide range of new data transmission methods over wireless channels must be developed, such as energy-efficient modulation and coding techniques, improved spectrum sensing, and radio resource management algorithms. New wireless transmission protocols for each network (LTE-A, Wi-Fi, M2M) must be developed in order to achieve full interoperability between them. The existing leading air interfaces, based on orthogonal frequency-division multiple access (OFDMA) and multiple-input multiple-output (MIMO) antennas, must be improved to fit the demands of future converged networks. There also must be a single signaling layer for the entire converged network in order to maintain quality of experience, even for high-mobility users. M2M devices are extensively used for metering, monitoring, and control in different areas, and the number of M2M devices is expected to be huge. However, in order to be cost effective, it is expected that such M2M devices must be simple, consume little power, and be reachable, robust, and able to integrate with different systems, such as TV, household appliances, alarm systems, smart-house systems, and cars. It is possible that during mobile network evolution toward 5G and 6G, the existing wireless transmission protocols may be replaced by new advanced and more efficient protocols.

Wireless Heterogeneity in Mobile Converged Networks

M2M in Mobile Converged Networks

M2M allows users to utilize multiple communication interfaces while sharing network access with other users. M2M networks usually use Wi-Fi or Bluetooth network protocols. However, Wi-Fi and Bluetooth protocols provide quite a lot less transmission capacity than cellular network protocols like LTE-A and Worldwide Interoperability for Microwave Access (WiMAX). Due to this limited capacity problem with M2M network protocols, the M2M and cellular convergence network will be one of the prospective hot research topics in the future. New spectrum reforming methods and algorithms were proposed due to utilizing the unlicensed spectrum for cellular networks [5]. As further development of M2M and cellular convergence networks, devices in the M2M network can share the unlicensed spectrum of cellular networks like LTE-A [6]. Thus, M2M can reduce the transmission load and significantly increase performance [7]. The four possible scenarios for M2M and cellular network convergence are presented in Fig. 2.

The first and simplest approach is the hotspot-based M2M and cellular convergence network in Fig. 2a. In this scenario, an M2M master node is selected from the criteria of maximum performance and battery level. The master device establishes the M2M area to be used to provide network access to other devices. Thus, in this type of M2M/cellular convergence network, the master M2M node utilizes all cellular resources, and shares them with other M2M devices. However, this scenario does not support any QoS control mechanisms. Thus, in this case, the probability of M2M network overload is relatively high if many devices are simultaneously connected to the master device. For quality support reasons, the mesh-based M2M and cellular convergence network scenario is preferred, because the convergence type uses the multihop connections in Fig. 2b. In this scenario, the master device connects only a limited number of devices. Furthermore, each device can be a secondary master, which can provide network multihop access devices. This mode allows the traffic between users to be balanced by managing data flows in the master M2M device. In this type of converged network, the M2M master device gets all the resources from the base station of the cellular network and shares them, particularly between M2M devices, through the unlicensed spectrum of cellular networks like LTE-A. The third scenario is the hybrid M2M and cellular convergence network, which can be organized by

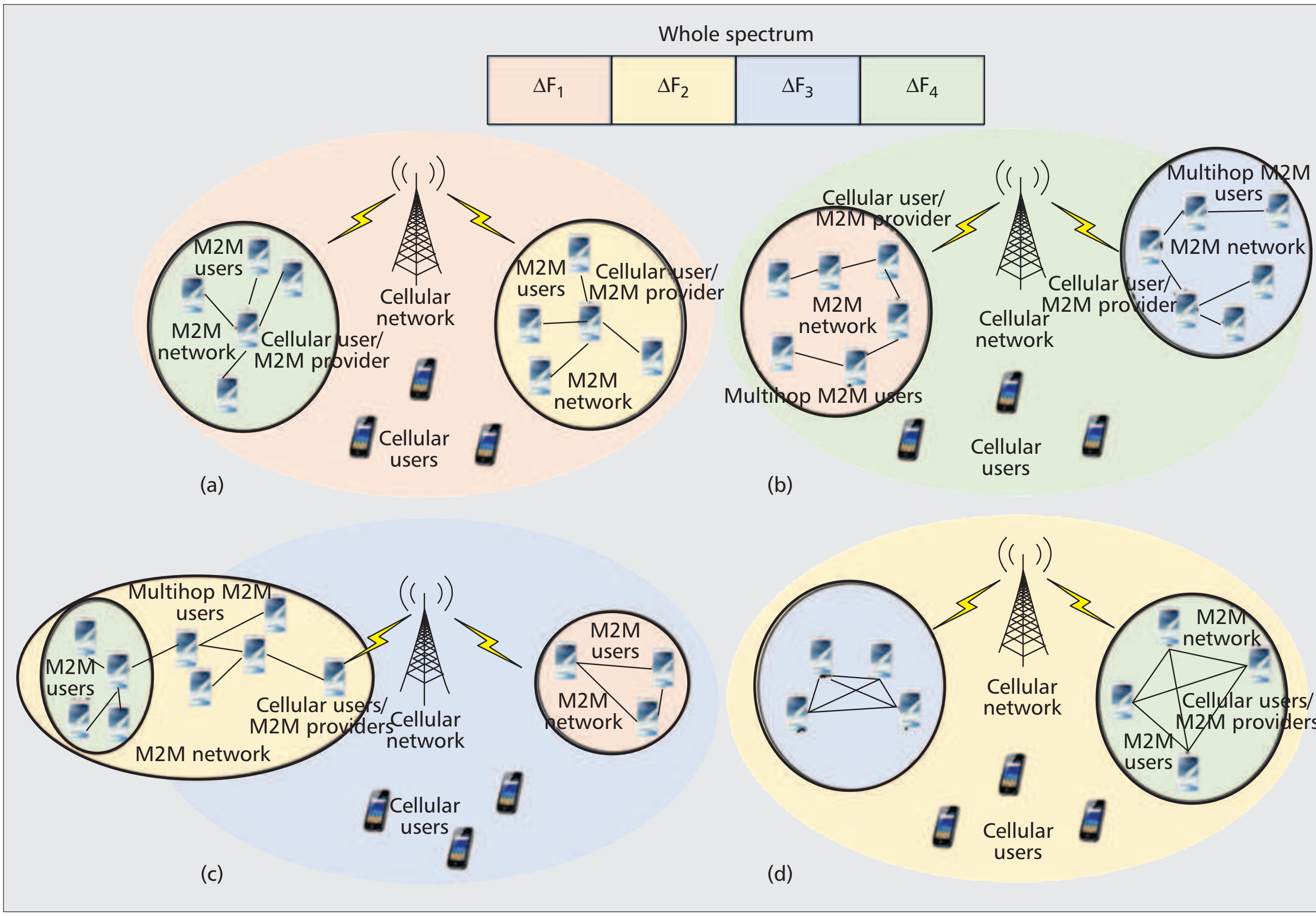

Figure 2. Converged mobile networks, including LTE-A, Wi-Fi, and M2M networks.

mesh topology as shown in Fig. 2c. This scenario supports hotspot-based M2M subnetworks with a master node connected by a multihop communication channel. In general, the scenario in Fig. 2c is combined from scenarios in Figs. 2a and 2b. This type of cellular/M2M convergence assumes that data flows may be distributed in accordance to the users' type of service. The most advanced scenario is a fully connected M2M network, which allows the use of multiple M2M connections for one data flow. With this feature for each transmission, optimal paths will be selected to achieve full unlicensed (Wi-Fi or Bluetooth) spectrum utilization. Moreover, this scenario is significantly different from previous ones, because all M2M devices may simultaneously be cellular consumers and M2M providers, thus increasing session reliability. Figure 2d illustrates a fully connected M2M network. Comparisons of the four possible M2M and cellular convergence network scenarios are summarized in Table 2.

Future Research Topics in M2M Technology

Future M2M networks will apparently be based on a fully connected topology, which can achieve the best performance. There are three important problems for future research topics that must be solved to fully utilize the advantages of this approach. First, the performance of end-user devices must increase in order to support multiple simultaneous connections. Performance increase assumes designing new end-user device architecture. The new architecture will be able to support ultra-wide frequency range, high-throughput M2M transmission methods, multiple antenna arrays, and great computing capabilities. Moreover, the current network protocol stack is not able to support interconnection between cellular networks and M2M underlay networks. Therefore, converged heterogeneous networks require a new protocol stack and a multiservice service-oriented platform in order to support emerging services such as ultra-high-definition video streaming, low-latency real-time applications, and mobile cloud computing services. An important issue for heterogeneous mobile networks is service quality assurance. Therefore, it is necessary to develop new algorithms for traffic management in mobile networks with different services and effective utilization of network resources. In [8], the advanced IP multimedia subsystem (IMS-A) architecture was proposed for converged heterogeneous mobile networks, which allows QoS provision with service differentiation. The further research topic in this field is to design new models for traffic balancing between M2M and cellular links to implement quality of experience (QoE) control policies. Second, the new algorithms should be designed for a converged mobile network's control plane. A promising solution for mobile network management is software defined radio access network (softRAN)

Interference limits network performance greatly. Therefore, the majority of future research into mobile convergence networks should be devoted to interference mitigation and the coexistence of different wireless standards.

M2M/Cell network convergence scenario	Advantages	Disadvantages
Hotspot-based M2M network	• Simple deployment • Simple session control • Dynamic channel utilization	• Possibility of overloading • Absence of quality control mechanisms • Low reliability
Mesh-based M2M network	• Traffic balancing • Multihop routes • Possibility of simple quality control	• Only static routes • Low reliability • Low channel utilization • Quality control mechanisms
Hybrid M2M network	• Dense traffic balancing • Multihop routes • Dynamic channel utilization	• Difficult deployment • Relatively low reliability • Only static routes
Fully connected M2M network	• Multipath traffic control • Precise quality control • Dynamic multihop routing algorithms • High reliability	• Difficult deployment • Complex session control • Complex routing control • Interference problem

Table 2. Comparisons of four different M2M/cell convergence network scenarios.

[9]. SoftRAN is a software defined centralized control plane for RANs that abstracts all base stations in a local geographical area as a virtual base station. The virtual base station comprises a central controller, a physical base station, and master devices of M2M networks. SoftRAN architecture provides load balancing and interference management, as well as throughput and traffic control. The third and most important problem to address is interference. Interference limits network performance greatly. Therefore, the majority of future research into mobile convergence networks should be devoted to interference mitigation and the coexistence of different wireless standards, which is addressed in the next section.

Interference Avoidance Problems in Mobile Converged Networks

M2M and Cellular Network Coexistence within the Same Spectrum

Establishing mobile M2M networks can achieve high spectral efficiency by unlicensed spectrum utilization and efficient radio resource management [10]. However, users' mobility and M2M network boundary uncertainty leads to a complex interference problem between different M2M networks and between M2M and cellular networks [11]. On the other hand, using different spectrum pools for separate M2M networks decreases the total capacity of a mobile converged network. As shown in Fig. 3, the most urgent problem in the M2M/cellular converged network is coexistence between cellular and M2M transmissions within one spectrum.

A simple and straightforward solution is for the transmission power of M2M devices to decrease within the M2M network. This will cause significant interference in neighboring cells when reusing the same frequency. On the other hand, decreasing cellular transmission power will lead to significant imbalance between uplink and downlink coverage. Using the existing solutions for interference mitigation in static LTE-A networks is not optimal due to different interference levels compared to a heterogeneous mobile network. Thus, other solutions will be needed and are addressed in the next section.

Coordinated Multipoint for Interference Avoidance

Co-channel interference management is of fundamental importance to allow direct transmissions between devices reusing radio spectrum of cellular networks. Coordinated multipoint (CoMP) is a promising solution able to mitigate and/or avoid high co-channel interference [12]. In fact, CoMP schemes will play an important role in allowing the coexistence of converged networks, M2M communications, and cellular networks within the same spectrum. CoMP will offer potentially high benefits for future wireless networks in terms of spectrum utilization and cellular coverage.

In CoMP systems, multiple transmission points are equipped with one or more co-located antennas interconnected by a fast backhaul (X2 interface for LTE-A). The fast backhaul allows multiple cells to coordinate their transmissions in order to improve signal strength and/or reduce intercell interference. The most common CoMP transmission schemes include coordinated scheduling/coordinated beamforming, and joint processing with joint transmission.

Coordinated scheduling reduces intercell interference among co-channel cells by scheduling users or silencing users. In other words, one cell can decide to assign a channel to a different user (scheduling) or even keep the channel unused (silencing) in order to reduce interference with neighboring cells. In a conventional system, the beamforming vectors in each cell are set independently. But in the coordinated beamforming system, the beamforming vectors for dif-

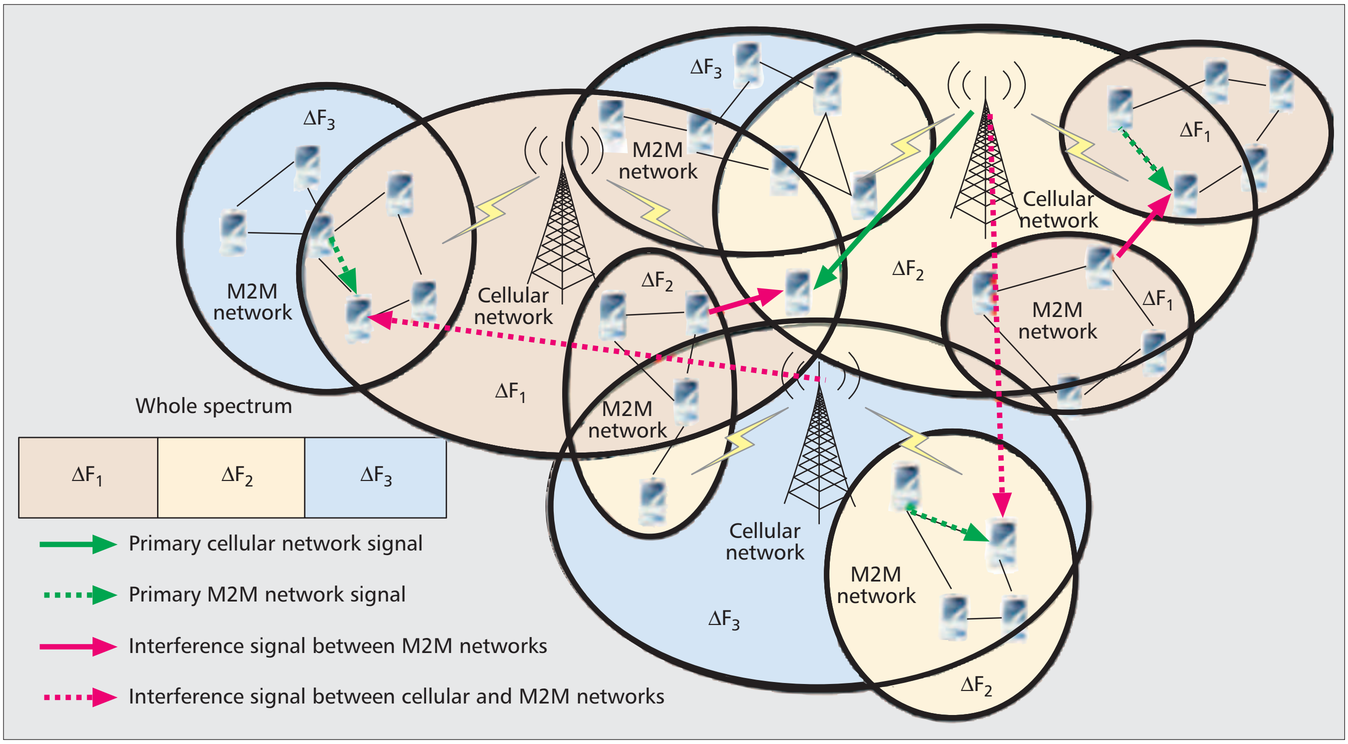

Figure 3. Spectrum reuse and interference within a converged mobile network of M2M and cellular networks.

ferent base stations are coordinated to aim at minimizing interference. For coordinated scheduling/coordinated beamforming, data of all co-channel users are not needed for all cooperating cells (or for a central controller, i.e., a fast backhaul). They require only a little information on scheduling decisions and channel quality of the users [13].

When a joint transmission is made, data and channel state information (CSI) of co-channel users are synchronously available to all cooperating cells (or to a central controller), and thus the transmit antennas work in a large multi-antenna system. The transmit antennas can jointly process signals using the well-known multi-antenna transmission schemes. One of the well-known multi-antenna transmission schemes is linear precoding. Linear precoding coherently combines signals of interest and suppresses interfering signals coming from different cells.

Distributed-Input Distributed-Output Wireless Technology

Distributed-input distributed-output (DIDO) wireless technology is a new revolutionary approach to multiuser data transmission in wireless networks. DIDO allows utilization of the entire spectrum by each user [14], in spite of sharing the same spectrum between many users. DIDO provides each wireless user with full data rate (in bits per second) of shared spectrum simultaneously with all other users by removing interference between users sharing the same spectrum. In traditional wireless technologies, the data rate available per user drops as more users share the same spectrum to avoid interference, but in DIDO, the data rate per user keeps the full data rate of the spectrum as more users are added. DIDO uses the cloud DIDO data center. The cloud DIDO data center controls all transmission sessions within wireless network. In DIDO systems, instead of interference avoidance, all wireless transmitters create interference artificially. Moreover, interference is a key part of DIDO networks, because all transmitted signals are summed in each receiver in clearly modulated waveform carrying the intended data for each device. First, DIDO transmitters exchange pilot test signals with DIDO receivers. By analyzing the results of these test signals' propagation, the DIDO data center precisely determines the channel conditions and calculates how the simultaneously transmitted signals will sum together in each receiver. Then the DIDO data center creates precise waveforms for all transmitters and stimulates interference between these signals. All signals will sum together at each user device, creating a clean independent waveform carrying the data requested by that user.

Future Research Topics of CoMP in Mobile Converged Networks

For future converged networks, a higher number of cells (macro-, micro-, pico-, and femtocells) are expected. Aside from their intrinsic advantages, CoMP schemes could be further used for converging networks to coordinate transmission on different scales, such as coordinating scheduling and/or orthogonalizing resources between different cell layers (e.g., macro- and femtocells). They can be achieved by clustering transmission points within a cell layer for joint processing or by coordinating different technology underlays between M2M and conventional cellular users. Most CoMP techniques consider a single tech-

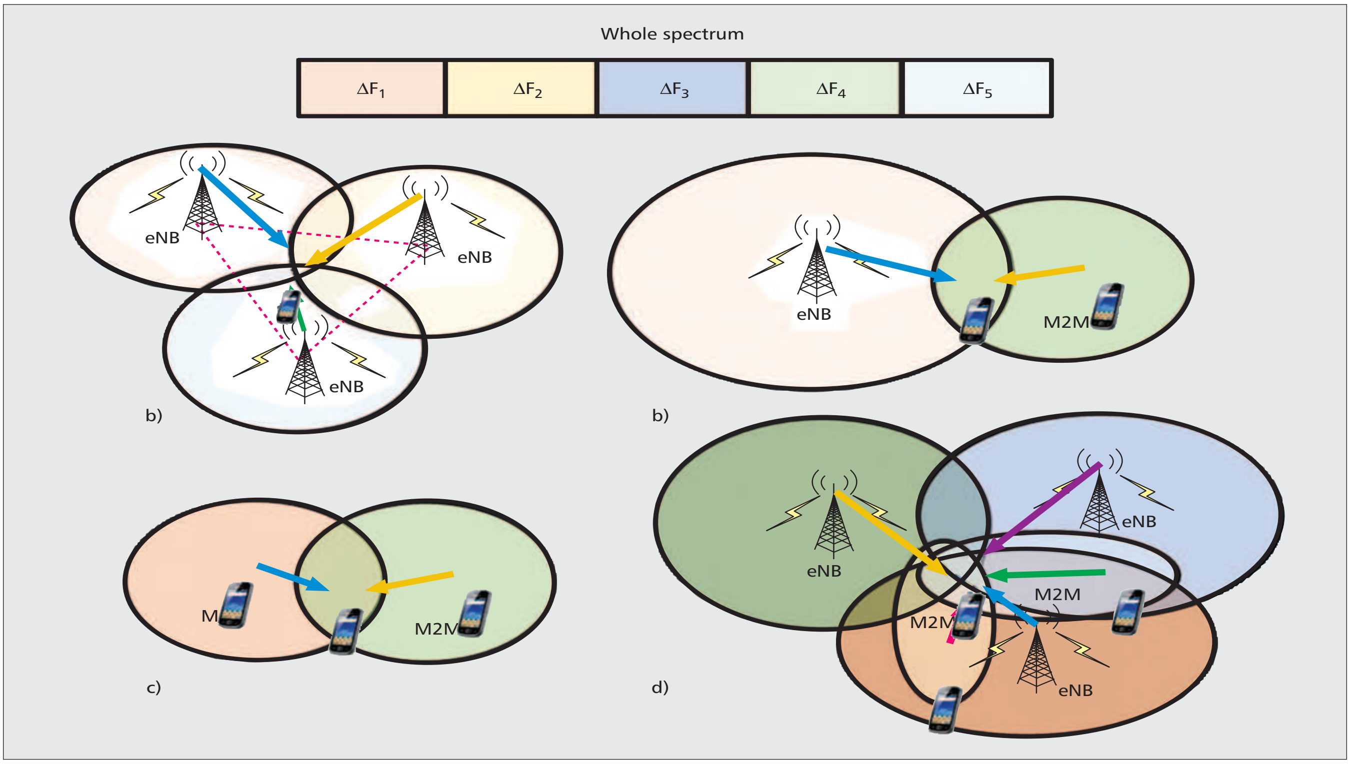

Figure 4. Possible uses of CoMP in mobile converged networks: a) conventional CoMP between cells; b) CoMP between cells and M2M; c) CoMP between M2M networks; d) CoMP between multiple cells and multiple M2M networks.

nology, but in converged networks, multiple technologies (LTE, Wi-Fi, etc.) will be used. Different CoMP uses within mobile converged networks are illustrated in Fig. 4. CoMP transmission schemes such as coordinated scheduling or coordinated beamforming, and joint processing may be employed in a cellular network in the future as illustrated in Fig. 4a. Figure 4b presents the kind of future CoMP scenario where users are able to simultaneously utilize cellular and M2M connections. This type of CoMP may be realized in different ways. As an example, uplink transmission may utilize cellular connection, while downlink uses M2M, and vice versa. Another scenario might use time-division or frequency-division duplexing for these purposes.

A further possible evolution of CoMP is simultaneous utilization of a few M2M connections, shown in Fig. 4c. This approach needs a precise data flow control protocol, and therefore will be useful only for fully connected M2M networks. Full convergence can be achieved with CoMP between all possible connections, shown in Fig. 4d. This type of CoMP is of great interest, because it will be able to combine LTE-A performance with WSN scalability, which perhaps will be a big step toward 5G mobile networks.

Another hot research topic is DIDO wireless networks. DIDO has already been tested at frequencies from 1 MHz to 1 GHz. The test results have shown extremely great performance. However, it seems obvious that increasing the number of DIDO users will sufficiently increase the complexity of separate waveforms calculation. Therefore, we assume that many future researchers will be devoted to designing new computing algorithms and signal modulation techniques for DIDO networks.

Case Study: M2M Communications Underlaying Cellular Networks by CoMP

Our case study illustrates potential spectrum utilization and coverage gains achieved by CoMP transmissions in the converged network of cellular and M2M communications sharing the same spectrum. The system-level simulation was conducted for a downlink OFDMA multi-cell system with an urban-microcell propagation environment, which is aligned with 3GPP LTE architecture. Further models and simulation parameters are detailed in [15].

To obtain resource reuse gains and exploit M2M proximity, M2M communications are only enabled in hotspot zones near cell edges, minimizing the impact on the performance of cellular communications [15]. For joint processing, we consider maximum ratio transmission (MRT) in the desired link with ideal channel state information. After resource assignment is carried out for cellular communications by the Proportional Fair (PF) scheduling policy, M2M devices are chosen based on the degree of cooperation. Two degrees of cooperation are considered in this simulation: CoMP between cells and M2M networks, and CoMP between M2M networks, respectively shown in Figs. 4b and 4c, detailed in the following.

CoMP between cellular and M2M connections are considered when a cellular user is scheduled inside the hotspot zone. Hence, an M2M device is randomly selected inside the

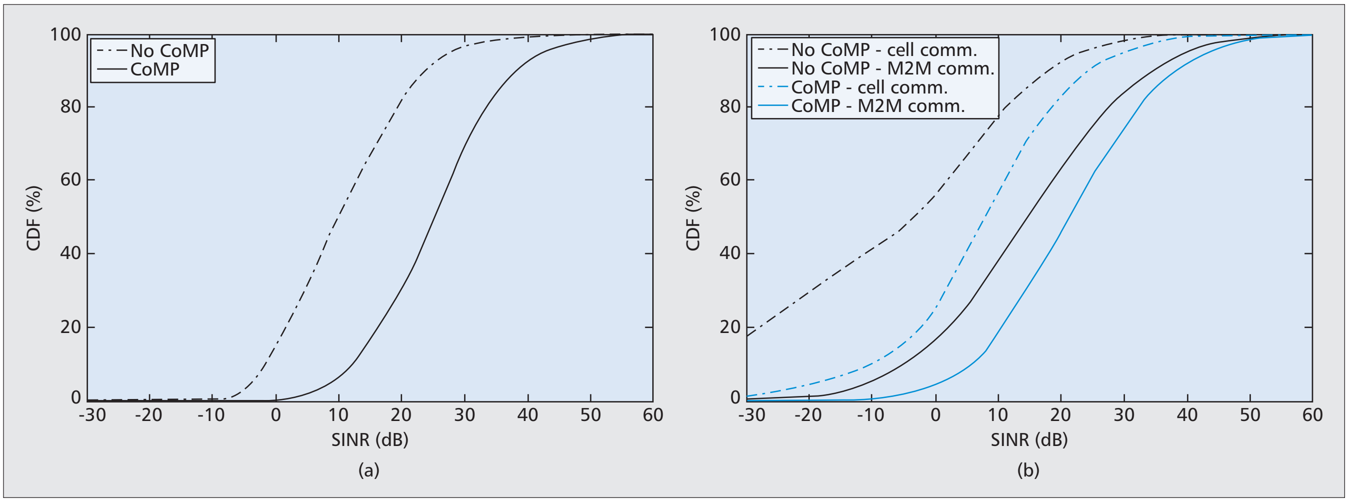

Figure 5. SINR levels of cellular and M2M communications for two CoMP schemes: a) CoMP between cells and M2M networks, and conventional scenario (No CoMP); b) CoMP between M2M networks, and M2M communications underlaying cellular networks (no CoMP).

hotspot for establishing a CoMP transmission. The conventional scenario, in which M2M communications are not enabled, is considered as a baseline.

CoMP between M2M connections is considered in every resource independent of the position of the cellular user. In this case study, two users with the same data to transmit and one receiver user are randomly selected inside the hotspot. As a baseline, the cellular user shares the same spectrum with an M2M communication between two devices in each cell.

Figure 5 shows the cumulative distribution function (CDF) of the signal-to-interference-plus-noise ratio (SINR) levels of cellular and M2M communications for both considered CoMP schemes. As shown in Fig. 5a, the performance is considerably improved using another closely located device to enhance the link quality perceived by cellular users. By comparing baseline scenarios in Figs. 5a and 5b, notice that there is a high negative impact on the performance of cellular communications due to M2M communications. Many cellular users are out of coverage with SINR levels below –6.2 dB, that is, the minimum target SINR to communicate [15] due to excessive interference generated by M2M communications. However, the performance of both M2M and cellular communications is improved when CoMP transmission is employed, as shown in Fig. 5b. While the gain with M2M communications comes from joint processing, the cellular gain happens because the energy conveyed by M2M transmitters is directed to the receiver, so the interference is weakened. Thus, CoMP transmission has been proven as a promising solution to protect cellular communications.

Spectral efficiency gains for CoMP communications in comparison to baselines of the CoMP scheme between cells and M2M networks are 75 percent. Spectral efficiency gains for CoMP communications in comparison to baselines of the CoMP scheme between M2M networks are 29 percent (meaning 83 percent of gains are for cellular networks). High spectral efficiency gains are achieved. However, it is important to highlight that this performance improvement comes at the cost of increased signaling and power consumption since more transmitters are involved in CoMP communication.

For future communication scenarios we consider CoMP as a promising approach for improving overall network performance. Combining the CoMP, M2M, and DIDO allows the new fully converged architecture of a wireless access network to be designed, where each transmission link will be established by using the optimal way for current network circumstances in order to achieve the best energy and spectral efficiency.

Moreover, software defined approaches can be implemented for the convergent mobile network, providing very flexible and convenient methods for 5G RAN management and service maintenance.

Conclusion

The evolution of current wireless mobile standards toward the next generation will require a soft convergence of heterogeneous mobile networks in order to provide users a unique and reliable mobile connection experience of different types or services regardless of their location, connection type, and device. This article has surveyed the key challenges and candidate solutions for the convergence of current wireless standards toward a heterogeneous mobile network scenario. Key problems related to the coexistence of the different wireless standards (cellular, broadcast, Wi-Fi, and Bluetooth) within the same spectrum band have been discussed. The integration of CoMP and M2M in a converged heterogeneous network entails a number of research challenges ranging from cell identification to physical and MAC layer problems such as interference coordination and scheduling. These issues open new perspectives for research in 5G wireless communications.

Through our case study, we have seen that CoMP transmissions in heterogeneous cellular and M2M networks offer high gains in terms of spectrum efficiency and coverage for mobile con-

Through our case study, we have seen that CoMP transmissions in heterogeneous networks, cellular and M2M networks offer high gains in terms of spectrum efficiency and coverage for mobile converged networks. Further spectral efficiency and QoS improvements might be achieved allowing for an intelligent (re)use of radio resources.

verged networks. Further spectral efficiency and QoS improvements might be achieved allowing intelligent (re)use of radio resources. Developing DIDO networks is of great interest in future research for 5G. The effective use of interference for distributed signal transmission will be a great solution for future 5G wireless networks.

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