Next generation cellular networks

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Abstract: The higher data rate (up to 100 Mbps) and strict quality of service (QoS) requirements of multimedia applications may not be fully supported over the current cellular networks. Since the transmit power of a data link increases with the data rate when a specific link quality is maintained, providing very high data rate services will require either the expenditure of high amounts of power or limiting the link to a short distance. Therefore, there are interests on investigating next-generation cellular network structures for higher data rates and coverage as well as scalability in addition to the continuing research on advanced wireless communication technologies. This decade is expected to bring many exciting changes to the wireless communication networks, enabling mobile broadband Internet services on a wide range of user devices. These changes are part of the wireless networks, evolution to fourth generation (4G) technologies. An overview of next generation cellular network is provided in this work including background and integration of cellular and Internet services. Next section deals with multihop cellular networks (MCNs) together with load balancing and cooperation in MCNs. Finally, the third part describes 4G cellular standards and reports on some research issues in this area.

Key-words: integrated services, multihop networks, IMT-Advanced systems

1 Introduction

Cellular networks have been developed for voice telephone service using circuit-switched technology. There are usually complex and large in terms of their network scale and operational features, high speed mobility, low delay rate, and wide area coverage. The aim of the process is to have an all-IP network architecture to provide high-bit rate multimedia services including voice, video and data [1]. Multimedia services require multiple sessions over one physical channel which could be provided by packet-switched networks. The common protocol set for packet switched networks is IP [2].

The 3G cellular technologies include UMTS (Universal Mobile Telecommunications System) and CDMA2000 (Code-Division Multiple Access). The UMTS evolved from the GSM (Global System for Mobile) network in Europe, and CDMA2000 evolved from CDMA. Both CDMA2000 and UMTS are defined by ITU (International Telecommunication Union) in IMT-2000 framework [3]. Based on the combination of circuit and packet switching, both CDMA2000 and UMTS combine mobile and IP technologies to provide personal communications and personalized content. A data session is established to carry IP packets between the network access server and the mobile node (MN) in both CDMA2000 and UMTS networks. Both networks use tunnels to support user mobility.

Several overlaid wireless networks including 3G networks, WLANs, and WMANs may exist over the same geographical area. IP mobility support for next generation heterogeneous mobile networks is shown in Fig. 1 [20]. The provision of authentication, authorization, and accounting (AAA) together with quality of service (QoS) control, are also provided.

Fig. 1. IP mobility support for next generation heterogeneous mobile networks.

Mobile IP version 6 (MIPv6) and its hierarchical mobility management extensions may provide a solution for internetwork mobility. The Internet and cellular systems have been designed and implemented by people with different backgrounds in computers and communications, respectively. Their integration can be considered a first step toward next
generation networks, where heterogeneous networks must work together in order to provide differential services to users in seamless and transparent manner. Next generation cellular networks are expected to provide richer and more diverse multimedia services. However, the current cellular network architecture may not be economically feasible to cater to the requirements of future mobile communication services.

As an alternative to cellular communications, ad hoc networking is a wireless communication technology distinguished by communicating via multihop transmissions. The multihop cellular network (MCN) which combines the characteristics of ad hoc networking with those of cellular network, has been drawing a lot of attention. Namely, MCN includes capacity enhancement, coverage extension network scalability and power reduction. The major motivation for integrating multihop transmission in cellular networks is to enhanced coverage and network capacity. Relaying can be used to assist communications to and from mobile hosts (MHs) at the cell edge or MHs experiencing deep fading in their home base station (BS).

This article starts with the background of the problem. Next, integration of cellular and Internet services including a cooperation in multihop cellular networks will be analyzed. Some examples will be included, too. Finally, 4G cellular standards, together with challenges conclude the presentation. It is pointed out that there are still a number of open research issues that need to be solved in order to provide an efficient and effective multihop transmissions in cellular networks in the future.

2 Background

The road to 4G runs through 3G networks. The Internet and cellular systems have been designed and implemented with different background in computers and communications, so their integration is an important task. The first generation (1G) cellular network was an analog circuit-switched system. Mobile handsets were bulky, voice quality was poor and security nonexistent. 2G networks improved on the disadvantages and provided additional data services like short messaging service (SMS). 2.5G is an intermediate step toward 3G, utilizing Internet protocols and packet switching in portion of the cellular network, but, unlike 3G, the 2.5 network is not Internet to the core [4]. 4G networks are a step beyond 3G providing data transmission speed equivalent to a local area network and more personalized services for its users.

Market conditions and technical realities dictate that future networks will be integrated and coexist with current ones. Thus 3G/4G networks integrate with the current crop of successfully deployed wireless communication systems.

Consider two examples concerning availability and service integration.

As for availability, when a cellular subscriber powers her Internet-capable phone, it can - using the Internet connection – inform a buddy list manager that turns her presence indicator to on. However, when the same cellular user initiates (or receives) phone call, the present system is unable to reflect for a current available status (i.e., busy). The reason is that the process of initiating (or receiving) a call uses different signaling protocols and a separate voice channel. Thus, it is impossible to derive an aggregate state of the subscriber based on only using one network, and its protocol.

The second example is the service integration. SMS allows a cellular subscriber to receive short text messaging on her cellular phone. However, if she does not have physical access to her cellular phone, or it is rendered inoperable, she cannot receive SMS messages destined to the phone. It should be possible for the subscriber to inform the cellular network, to make intelligent decisions on her behalf such that the SMS is converted to an Internet instant message and routed to her Internet-connected personal assistant (PDA) in real-time.

3 Integration of cellular and Internet services

A standard-based approach for an integration of cellular and Internet services can be obtained by using the wireless intelligent network (WIN) standards [5]. WIN specifies the capabilities and protocols used by all participating entities in the cellular network. For the Internet, SPIRITS protocol as a proposed standard by the IETF (Internet Engineering Task Force) is used in [6]. WIN provides an effective service platform for services executing in the cellular network. However, the current trend points toward providing services on the Internet. The integration architecture and its implementation is shown in Fig.2. The network infrastructure consists of cellular phones, mobile switching center MSC, home location register HLR, visitor location register VLR, service control point SCP, short message service center SMS-C. The goal of this architecture is to provide services that further integrate the Internet and the cellular network. The
The centerpiece of the architecture is the event manager which straddles both networks. It insulates the cellular network entities from Internet protocols. Also, it is responsible for authenticating use agents and maintaining subscription state.

There exists interest in integrating multihop relaying functionalities into cellular wireless networks. Multihop cellular networks can potentially enhance coverage data rates, QoS performance in terms of call blocking probability, bit error rate, as well as QoS for different users. The next generation cellular wireless networks will support high data rates and provide QoS for multimedia applications with increased network capacity. Under limited frequency resources, the conventional approach to increase network capacity is to install more base stations (BSs) to exploit spatial reuse. Because of cost of the BS transceiver which is quite high, this solution is not very efficient. An alternative approach is to employ relay stations (RSs) as intermediate nodes to establish multihop communication paths between mobile hosts (MHs) and their corresponding BSs. This has spurred increasing interest in developing new architecture and corresponding protocols for future generation multihop cellular networks (MCNs). Existing architectures and protocols for MCNs are different. RSs can be preinstalled by network operators [8] or be other idle MHs who are not transmitting their own data [9]. Depending on how radio resources are allocated for routing paths of active connections, different protocols at the medium access control and routing layers can be designed. Radio resources for MHs at different hops may be allocated in time division duplex (TDD) or frequency-division duplex (FDD) mode. Frequency bands other than the cellular frequency band may be used for relaying [10]. Advanced techniques using cooperative diversity can be employed to enhance network performance compared to simple relaying schemes [11, 12].

In order to balance traffic load among highly loaded (hot) cells and lightly loaded (cool) cells, relaying can be proposed as it is presented in Fig.3 [13]. Primary and secondary relaying schemes are presented, too. It was assumed that each cell is assigned a finite number of channels. Preinstalled RSs are available to regulate traffic from hot cells to cool cells using transmission in unlicensed frequency bands. Each RS and MH are equipped with two air interfaces, a C (cellular) interface for communications with a BS, and R (relaying) interface for communications with MHs or other RSs.
In a conventional system, if an MH wishes to establish a new call and cannot find and available channel in its home BS, it is blocked. In a multihop cellular network MCN using primary relaying, this MH switches to its R interface and establishes multihop communication with a neighboring BS through multiple RSs.

For example, if MH2 (Fig.3) cannot find an available channel in its congested BS A, it will try to communicate with the noncongested BS B through RS1 and RS2. On the other hand, RS2 communicates with BS B by using its C interface on a channel allocated by BS B. If a new call cannot be diverted from a congested cell to neighboring cells, primary relaying is not possible. Thus, the secondary relay scheme will be activated, i.e., secondary relaying will be used. A new call initiated by MH could not be accommodated by either BS A or its neighboring cells using the primary relaying. In this case, an ongoing call from MH1 may be diverted to BS B by using multihop connection through RS1 and RS2. The channel allocated for MH1 is released and reallocated to MH2. The implementation of these two relaying schemes reduces call blocking probability significantly from the case where no relaying scheme is employed as in conventional cellular networks.

Also, QoS fairness in terms of call blocking probability by balancing traffic among congested and noncongested cells is improved. This is most suitable for time-division multiple access (TDMA)-based cellular systems.

5 Cooperation in multihop cellular networks

Cooperative wireless communication systems require the incorporation of relay terminals into cellular networks and also need multihop transmission due to the half duplex nature of wireless terminals. Cooperative communication schemes can provide enhancements in terms of end-to-end throughput even if they require additional expenditure of radio resources arising from the need for multihop transmissions. All these schemes necessitate two-phased (two-hop) communications as the relay station (RS) needs to be informed of the signals that are transmitted by a source terminal. The cooperative schemes adopted in multihop cellular networks include: cooperative multiple-input multiple-output, cooperative multiple-input single-output, cooperative single-input multiple-output, conventional relaying.

- In cooperative multiple-input multiple-output, the mobile station (MS) and relay station (RS) listen to the transmission of the base station (BS) during the first phase. In the second phase, both (BS) and RS transmit simultaneously using the same radio source. Hence, the cooperative space-time coding can be used. If the MS can combine the received signals during the first and second phase appropriately, it can benefit from cooperative diversity.

- In cooperative multiple-input single-output, only the RS listens to the transmission of the BS during the first phase. In the second phase, both BS and RS transmit simultaneously using same radio resource. Hence, cooperative space-time coding can be used. If the MS can combine the received signals from the BS and RS, it can benefit from cooperative transmit diversity.

- In the case of cooperative single-input multiple-output, the MS and RS listen to the transmission of the BS during the first phase. In the second phase, only the RS transmits. It relays the signals it has received during the first phase. If the MS can combine the received signals during the first and second phase appropriately, it can benefit from cooperative receive diversity.

- In the first phase of conventional relaying, the RS receives the transmissions of the BS that are destined to a given MS. In the second phase, the RS simply forwards to the MS the signals it has received during the first phase. This scheme provides only path loss savings, whereas cooperative schemes provide diversity gain as well.
6 IMT-Advanced systems
This time expected to bring many changes to the wireless communication networks, enabling true mobile broadband Internet services on a wide range of user devices. These changes are part of the wireless networks evolution to fourth generation (4G) techniques and networks in line with IMT (International Mobile Telecommunication)-advanced technology requirements and definitions in the Radio Sector of the ITU-R (International Telecommunication Union).

The evolution to 4G/IMT-Advanced systems enables new services and usage models with the higher efficiencies of a highly self-configurable network infrastructure. These challenges should be met with simpler Internet-friendly and flat network architectures that make the best use of multiple bands and multiple carriers in licensed and unlicensed spectrum to provide broadband quality of experience at competitive cost.

The multihop relaying method for cellular wireless networks was considered by 3GPP (Third Generation Partnership Projects) under the name opportunity-driven multiple access (ODMA) [14]. Spectral efficiency and robustness against multipath impairments are two major advantages of orthogonal frequency-division multiplexing (OFDM). When applied in OFDM-based wireless networks, cooperative schemes can be used at each subchannel comprising several frequency diverse subcarriers. The orthogonal frequency-division multiple access (OFDM)-based on IEEE802.16 standard is developed for providing broadband coverage for mobile users in single-hop wireless metropolitan area network [15]. This standard is also referred to as mobile WiMAX.

Two main 4G standards are IEEE802.16m (WiMAX) and 3GPP Long Term Evaluation (LTE). Most 4G systems including WiMAX 802.16m [16, 17], are targeting single-frequency deployments. Frequency reuse results in a significant increase in system capacity. Also, it degrades the performance experiences by cell edge users due to the increased interference caused by out-of-cell transmissions. Signal-to-interference-plus-noise radio (SINR) distribution for a network with multiple frequency reuse factors (500m cell) is shown in Fig.4 [19].

Degradation in SINR for Reuse 1 relative to Reuse 3 is approximately 10 dB. While the increase in capacity due to the availability of increased bandwidth can offset the capacity loss due to SINR degradation, the capacity of users with very weak SINR (cell edge users) still degrades. Hence, interference management schemes are critical to improve the performance of cell edge users. Therefore, both 802.16m schemes and 3GPP-LTE, have focused on several interference management schemes for improving system performance. These techniques include semi-static radio resource management (RRM), through adaptive fractional frequency reuse (FFR) mechanisms, power control, and smart antennas techniques to null interference from other cells.

While in details WiMAX and LTE have somewhat different designs, there are many concepts, features, and capabilities commonly used in both systems to meet a common set of requirements and expectations. For example, at the physical layer both technologies deploy orthogonal frequency-division multiple access (OFDMA)-based designs combined with various modes of multiple-input multiple-output (MIMO) configurations and fast link adaptation with time frequency scheduling. Also, medium access control (MAC) of both systems support multicarrier operation and heterogeneous networks of cells, consisting of a mix of macrocells, femto cells, and relay nodes, which bring all kinds of challenges and solutions for mobility, interference, and traffic management.
7 Research issues

There are some research issues related to designing multihop networks (MHNs). Research problems are involved in both relaying and cooperative transmission strategies. The research problems center around challenges in developing routing and resource allocation schemes for MCNs.

The fundamental question in any relaying strategy in an MCN is how to perform joint resource allocation and routing such that maximum performance gains in terms of network capacity, coverage and QoS performance can be achieved. Resource allocation depends on the physical layer design where either time-division duplex (TDD) or frequency-division duplex (FDD) is employed for transmission on different hops of each routing path between mobile host (MH) and its corresponding base station (BS). Also, it depends on whether out-of-band relaying is employed or not as well as how many interfaces each MH carries. Generally speaking, resource allocation should be done such that the best trade-off between spatial reuse gain and capacity reduction due to interface effects can be achieved. The design of a joint resource allocation and routing scheme should be done such that the congestion level is low enough, while the desired QoS performance in terms of bit error rate (BER) or signal-to-interference-and-noise ratio (SINR) can be achieved.

When cooperative diversity is employed, several research issues arise in different layers of the protocol stack. Here, the resource allocation, clustering and routing problems should be tackled jointly. As in the relaying schemes, interference should be carefully considered in solving this joint problem. At the physical layer, several design implementations can be considered to achieve the potential diversity gain from cooperative diversity. To realize a distributed space-time code or distributed phased array (beamforming) technique can be employed to realize the diversity gain. Space-time code implementation, which is a specific implementation of the decode-and-forward scheme, is challenging because of the distributed nature of relay nodes [18, 19]. In addition, development of an optimal space-time code is still an active research area. Also, beamforming implementation, signalization of simultaneous transmissions from multiple relay nodes for coherent summation of their signals at the receiving side is a challenging task.

Important future research areas for the design of OFDM-based multihop cellular networks include:

- design of fully adaptive relaying schemes,
- link adaptation and end-to-end throughput performance evaluation,
- timing and frequency offset estimations,
- resource allocation,
- hardware testbed development,
- design of MIMO-OFDM receivers.

Efficient adaptive relaying schemes should be designed to improve the spectral efficiency of the network.

Efficient link adaptation mechanisms should be developed, and then the end-to-end throughput performance of multihop cellular networks should be evaluated. These issues should be explored with realistic channel models.

Timing and frequency offset estimations are critical for the satisfactory performance of OFDM-based multihop cellular networks. Based on these facts, efficient synchronization algorithms to be used at the terminals can be developed.

Efficient OFDM subcarrier allocation strategies should be developed. Otherwise, the improvement in spectral efficiency promised by relaying cannot be optimized.

Also, hardware testbed development must be carried out. In order to fully explore cooperative diversity related issues, implementation models of elementary OFDM-based relay network nodes need to be developed and physically, implemented on a selected hardware platform. This will allow to verify the theoretical benefits of using cooperative diversity in OFDM-based multihop networks and further develop practical methods for improving transmission efficiency.

When realistic assumptions are made instead of the usual idealistic assumptions, many factors like the impact of fast fading, feedback delay, imperfect channel estimation and imperfect synchronization require further research. All these factors must be taken into account. When designing MIMO-OFDM receivers, the introduction of multiple antennas at any terminal of a relay network can improve the end-to-end performance.
8 Conclusions

Traditional cellular networks are expecting to support not only mobile telephony services, but also next generation multimedia applications, such as voice over IP, video and audio downloads and playback, mobile TV, interactive games. Next generation cellular networks provide richer and more diverse multimedia services such as mobile Internet, video conferencing and mobile gaming, with much higher data rates even up to 1 Gbps. The current cellular network architecture may not be economically feasible to cater to the requirements of future mobile communication services. As an alternative to cellular communications, ad hoc networking is a wireless communication technology distinguished by allowing nodes to form an infrastructure less network by communicating via multihop transmissions.

Multihop cellular network (MCN) combines the characteristics of ad hoc networking with those of a cellular network. This network incorporates the flexibility of ad hoc networking, while preserving the benefits of using an infrastructure. The advantages of using MCN include capacity enhancement, coverage extension, network scalability and power reduction. Compared to cooperative relaying cellular networks, MCNs can fully utilize the advantages of multihop ad hoc networking techniques. It can efficiently reduce network infrastructure investments and improve the overall network performances (bandwidth utilization, network coverage, flexibility and scalability).

Two main 4G radio standards are: IEEE802.16m (WiMAX), and 3GPP-Long Term Evaluation (LTE). While in details WiMAX and LTE have somewhat different designs, there are many concepts, features and capabilities commonly used in both systems. For example, at the physical layer both technologies deploy OFDM-based designs combined with various modes of MIMO configurations and fast link adaptation with time-frequency scheduling. Also, medium access control (MAC) of both systems supports multicarrier operation and heterogeneous networks of cells, which bring all kinds of challenges and solutions for mobility, interference and traffic management.

4G cellular standards are targeting frequency Reuse 1 (aggressive spectrum reuse) to achieve high system capacity and simplify radio network planning. The increase in system capacity comes at the expense of SINR degradation due to the increased intercell interference, which severely impact cell-edge user capacity and overall system throughput.

References:

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