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RESEARCH ARTICLE

A study of multi-hop cellular networks[†]

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ABSTRACT

The number of cellular communication subscribers continues to grow, attesting to the great success of this technology. However, cellular networks have inherent limitations on cell capacity and coverage and shortcomings such as the dead spot and the hot spot problems. Multi-hop cellular networks (MCNs) help enhance the cell capacity and coverage, while, at the same time, alleviating the dead spot and hot spot problems, increasing the utilization of radio resource, and reducing the power consumption of mobile terminals. In the past decade, more than a dozen of MCN architectures were proposed. In this paper, we study various types of MCN proposals. We identify and discuss the design decision factors and use these factors to classify most existing MCN proposals. Future research directions, including studies of capacity and energy consumption, and approaches addressing design issues such as cell size, routing, channel assignment, load balancing for MCNs are discussed. Copyright © 2010 John Wiley & Sons, Ltd.

KEYWORDS

survey; multi-hop; cellular networks; architecture; design factors

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1. INTRODUCTION

Wireless communication technology has made great gains in popularity over the past decade and will be playing a more important role in access networks, as evidenced by the widespread adoption of cellular networks, wireless local area networks (WLANs) and worldwide inter-operability for microwave access (WiMAX). A common feature of these wireless technologies is presence of a base station (BS) and central control. Users of these wireless access networks expect high quality, reliability, and easy access to high-speed services anytime, anywhere, and in any form.

In cellular networks, however, inherent limitations on cell capacity and cell coverage exist. Due to the capacity limitation, in dense areas known as *hot spots*, such as downtown areas and amusement parks, subscribers tend to experience higher call blocking. Mobile terminals (MTs) which are outside the transmission range (coverage) of the BSs are not able to access the networks. Even though they are within the transmission range of the BS, there are still some areas where coverage is yet to be provided. These areas are often referred to as *dead spots*, which include indoor environments, and underground areas, where a strong shadowing effect exists. A possible solution is to install more BSs or repeaters in congested and/or poorly covered and/or out of reach regions. Multi-hop cellular networks (MCNs) can be an alternative or a complementary method to BSs and repeaters. In this case, individual terminals in areas where BS coverage cannot be attained, relay their messages via one or more MTs and/or special stationary devices that have a direct or indirect link to the BS. MCNs also allow a higher transmission rate (cell capacity) due to the short transmission range [1,2]. Hot spots can be eased by relaying the load to their neighboring less-congested or non-congested cell through other MTs or relaying devices [3].

MCNs have the potential to enhance the cell capacity, extend the cell coverage, and alleviate the hot spot and the dead spot problems. In addition, MCNs provide faster deployment, fewer infrastructure requirements, and peak power consumption reduction. Therefore, MCNs can be more economically desirable. In fact, due to these potential benefits, there has recently been an interest in deploying this technique in cellular networks, particularly for the third generation (3G) wireless systems [1]. In this paper, we study a number of different proposals of MCNs. We identify and discuss the design decision factors for these networks and classify the existing MCN proposals based on these factors. Future research directions, including capacity and energy

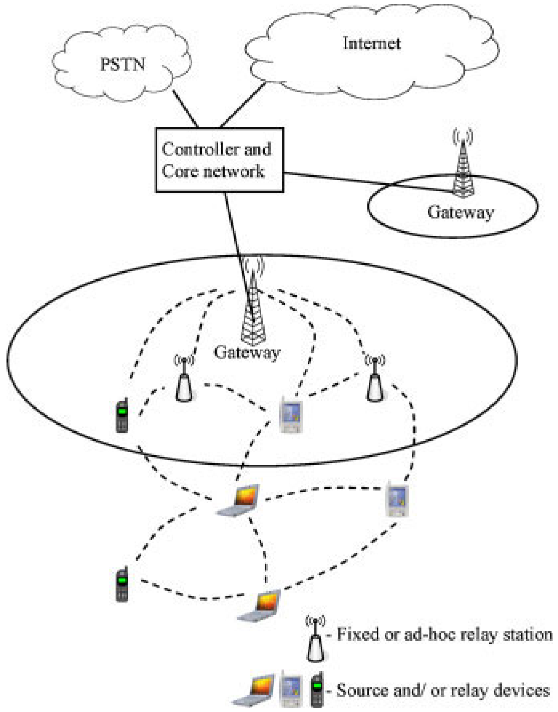


Fig. 1. Network architecture for MCNs.

consumption studies, approaches addressing design issues such as cell size, routing, channel assignment, load balancing, etc., are also discussed.

This paper is organized as follows. In Section 2, we briefly describe the network architecture of MCNs and various types of wireless technologies that are potential candidates for the core technology of these networks. In Section 3, we present and discuss the design decision factors. A classification of existing MCN proposals based on these factors are presented. In Section 4, future research directions, issues, approaches, and research challenges facing these networks are discussed.

2. NETWORK ARCHITECTURE

The architecture of MCNs consists of cellular and *ad hoc* relaying components. Signals of mobile nodes are relayed through a relaying device to a gateway device. Signals are then sent through a network controller (a mobile switching center (MSC), a radio network controller with a core network, or a router) to the public switching telephone networks (PSTN), the Internet, or other networks (see Figure 1). A gateway device is typically a cellular BS. A relaying device can be a stationary dedicated repeater, wireless router, or MT. If MTs are used for relaying, the MCNs are basically a hybrid of cellular networks and *ad hoc* networks. Having a hybrid network architecture, MCNs gain the benefits and inherit the weaknesses of both cellular networks and *ad hoc* networks.

In general, the wireless technology for MCNs is not limited to the cellular technology, such as second generation (2G) or 3G, but extends to infrastructure-based wireless networks such as WLANs and WiMAX. In fact, there are MCN proposals designed based on WLANs technology or a combination of the technologies described above.

Cellular networks provide large coverage and high quality voice and data communications, but require high cost of infrastructure and licensed frequency bands, whereas WLANs provide small coverage only, but the cost is low because the devices are cheap and the license-free industrial scientific and medical (ISM) bands can be used. WLANs also allow a high-data rate if the number of users is small and interference from other WLANs is little. Note that although the latest WLAN standard, IEEE 802.11, has the option of providing quality of service (QoS) guarantee, the QoS provisioning could be affected by the interference from other nearby devices and/or WLAN which use the same ISM band channels. WiMAX has similar features as that of cellular networks except providing high quality voice communications, but the infrastructure required is cheaper. In cellular networks, 3G provides medium data rates and high frequency reuse. However, it is based on code division multiple access (CDMA) which is an interference-limited technology and requires power control to minimize the interference among cells and within cells to maintain a high level of cell capacity and to avoid mobiles, which are close to the BS, dominating the reception of the BS (near-far problem). *Ad hoc* networks have the advantage of flexibility and are cost efficient. However, they are characterized by frequent network disconnections due to mobility and limited battery life of mobiles, and usually require routing protocols to route the packets from source nodes to destination nodes. For infrastructure-based single-hop wireless networks, routing protocols are not required for wireless access because mobile nodes communicate with the BS or access point (AP) directly. Table I summarizes the characteristics, limitations, and problems of these networks.

3. DESIGN FACTORS AND ISSUES

Although MCNs are basically hybrids of infrastructure-based networks and *ad hoc* networks, there are a number of decision factors that affect the design of MCNs. Some important factors are wireless technology, cell size, relaying device, wireless interface, communications mode, supporting technology, routing strategy, channel assignment, and load balancing. Table II depicts the design decision factors, and related issues. Figure 2 shows the classification of major existing MCN proposals based on a combination of the design decision factors. For example, integrated cellular and *ad hoc* relay (iCAR) [3] is designed for any cellular system assuming WLANs technology for *ad hoc* relay access. A medium to large cell size is used. Limited mobility *ad hoc* relay stations (ARSs) are placed at strategic locations to facilitate traffic relaying. These devices are equipped with two interfaces: one for communicating with the BS using

Table I. Characteristics of various types of cellular and *ad hoc* networks.

	Infrastructure-based networks				
	3-3.5 G	2 G	WiMAX	WLAN	*Ad hoc* Networks
Systems	Centralized				Distributed
Flexibility	Low				High
Gateway device	BS			AP	None
Infrastructure cost	High		Medium	Low	Low
Capacity (data-rate)	Medium to high	Low	Medium to high	High	Variable
Transmission power	High to low			Low	Low
Cell size (range)	Large to small			Small	n/a
Frequency band	Licensed		Licensed, ISM	ISM	ISM
Reliability	High			Medium	Relatively low
Medium access	Multiple access			Contention based or -free	Contention based
Air interface technology	Interference limited		Bandwidth limited		Bandwidth limited
Overhead	Handoff			Medium contention	Routing, medium contention
Channel reuse	Low			High	High
Routing	Not required (between MT and BS)				Required
Load balancing	Release BS congestion			n/a	Release MT congestion
Quality of service (QoS)	Easy to assure	n/a	Easy to assure	Not easy to assure	Difficult to assure
Limitations	Cell capacity, cell coverage				Limited battery life, topology
Problems	Hot spot, dead spot				Frequent disconnection, signal collision
	Near-far	–	–	–	

n/a, not applicable.

licensed bands whereas the other one for communicating with ARSs using ISM bands. Centralized routing scheme is executed at MSCs whereas a combination of hierarchical and flat routing strategy is used. No channel assignment scheme is proposed for this architecture. Balancing load among BSs is a main propose of this scheme. No supporting technology, such as global positioning system (GPS) or directional antennas, is assumed. Other MCN proposals such as, cellular aided mobile *ad hoc* network (CAMA) [4], self-organizing packet radio *ad hoc* networks with overlay (SOPRANO) [5], virtual cellular networks (VCN) [6], and WiMAX mobile multi-hop relay (IEEE 802.16j) [7] can also be classified based on the design factors. In the remainder of this section, we discuss these design decision factors and related issues.

3.1. Wireless technology

Wireless technology is a main design decision factor for MCNs because it raises a number of important issues including cost, capacity, coverage, QoS, channel assignment, and power control.

Choosing cellular technologies for implementing MCNs implies high infrastructure cost, low to medium cell capacity, small to large cell size, good QoS provisioning, and more reliable and secure services. In cellular (2G and 3G) networks, channel assignment is required for source nodes. In MCNs, channel assignment would be also required for all relaying nodes as well as source nodes in the network, making the assignment more complex. If 3G is chosen, power control issue also arises because CDMA technology is used. Cellular technology requires licensing for frequency spectrum which may not be available due to spectrum limitation, political and/or national security reasons. In addition, the high licensing cost is eventually transferred to end-users.

Choosing WiMAX for MCNs has similar benefits and issues to these of cellular technology in terms of cell size, QoS provisioning (except voice quality), and channel assignment, but lower BS cost compared to that of cellular systems. In addition to licensed frequency bands, WiMAX can be operated on license-free ISM bands. This advantage eases the spectrum requirements of WiMAX operators. However, other issues, such as initial infrastructure cost and the progress and pricing of other competing technologies, would affect the success of WiMAX.

WLAN is a low-cost option for MCNs because APs are cheap and no frequency-licensing fee is required. Spectrum availability is not an issue because ISM bands are readily for use. Using WLANs implies low cost, high data-rates, but small cell size due to restricted transmission power level, no QoS guarantee due to unknown interference condition. In high interference condition, signal senders are required to back-off and retransmit their packets. This overhead greatly degrades the network performance in terms of throughput and delay and makes QoS even harder to be assured.

A combination of cellular and WiMAX and/or WLANs is a possible option. In this case, licensed bands can be used together with ISM bands. This is especially convenient when extra licensed bands for relaying are not available. Licensed bands are used for cellular access whereas ISM bands are used for *ad hoc* relaying. An added advantage to such setting is that the signals of the relaying component do not interfere with the signals of the cellular commu-

Table II. Design decision factors and related issues for MCNs.

Wireless technology	Cell size	Relaying device	Wireless interface	P2P mode	Supporting technology	Routing strategy	Channel assignment	Load balancing
Cost, capacity, coverage, QoS, channel assignment, power control	Cost, capacity, coverage, utilization, throughput, routing, packet delay	Cost, reliability, flexibility, security, node placement	Cost, complexity, interference	Complexity	Cost, reliability	Delay, throughput, QoS	Channel reuse, interference, delay, throughput	Cost, flexibility, overhead

nications. The disadvantage is that QoS of the relaying component cannot be assured.

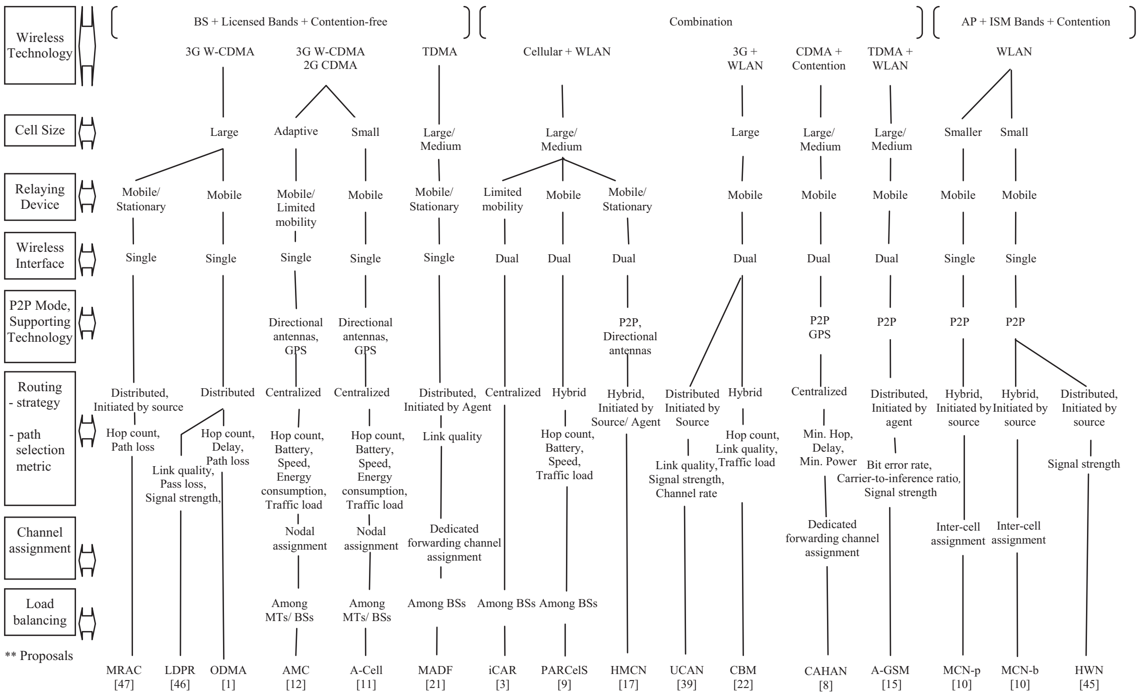
Another option of combining technology is to assign some cellular channels for contention-based access for the relaying component. This way, interference from users of ISM bands can be avoided. Cellular *ad hoc* augmented networks (CAHAN) [8] is an example based on this idea.

For MCNs, cellular or WiMAX technology seems to be a better choice in terms of capacity, coverage, QoS provisioning, reliability, and security. However, channel assignment and power control (if CDMA system is used) issues need to be addressed. In addition, cell size significantly affects the system throughput and resource utilization of the networks. More discussions on these issues are as follows and in Section 4.

3.2. Cell size

Cell size affects the cell or system capacity and network reachability which, in turn, affects the radio resource utilization, routing efficiency, packet delay, and hence, system throughput. While the cell size of WLANs is typically fixed and small, the cell size is controllable in cellular or WiMAX based MCNs. This makes cell size an important design decision factor.

In interference-limited systems, such as 2G-CDMA or 3G, a smaller cell size or shorter transmission range requires lower transmission power to transmit signals. This reduces the interference within a cell and thus, enhances the cell capacity in term of data-rates. This is one main motivation for proposing the opportunity-driven multiple access (ODMA) [1]. In a bandwidth-limited system, such as 2G time division multiple access (TDMA) or WiMAX orthogonal frequency division multiple access (OFDMA), a small cell size allows higher frequency reuse among cells and hence, a higher system capacity. However, a small cell size reduces the network reachability. If there are not enough relaying nodes, source MTs has low chance to have relaying paths to relay their signals to the BS. Thus, even though abundant cell capacity is available in the cell, MTs simply cannot reach the BS to use the capacity. This would greatly reduce the utilization of radio resource. To avoid directly addressing the reachability issue, most MCN proposals assume either a large cell size, e.g., in iCAR [3] and pervasive *ad hoc* relaying for cellular systems (PARCelS)[9], or a small cell size with a dense network, e.g., in multi-hop cellular network with power reduction (MCN-p) [10] and *ad hoc*-cellular (A-Cell) [11] architecture. Assuming large cell size sacrifices the benefit of cell capacity enhancement using a small cell size whereas the assumption of a small cell size with high-node density may not always be the case in practice. How to achieve a good balance between cell size, cell capacity, and network reachability, given a network topology, network density, and traffic patterns to achieve maximum throughput in MCNs is an interesting and important topic. The cell size issue has not been addressed until, recently, an adaptive cell size architecture called adap-



** Full names of proposals are in Appendix.

Fig. 2. Classification of some MCN proposals based on the design decision factors.

tive multi-hop cellular (AMC) [12] was proposed. A brief discussion on AMC is provided in Section 4.3.

Cell size also affects the routing efficiency and hence, the packet delay. An initially large cell size allows route discovery or update to reach all MTs in single-hop communication. After a route is set-up or updated, a small cell size (allowing a higher capacity through multi-hop short-range relaying path) can be used for actual data communications. A-Cell adaptive routing (ACAR) [13] is designed based on this idea. This approach is discussed in Section 4.4.

3.3. Relaying device

A relaying device helps forward the signals of a source node to a BS, an AP, or other MTs. The device can be carrier-owned or user-owned. Choice of device involves a trade-off between cost and reliability on the one hand and flexibility, security, and node placement on the other.

Carrier-owned devices can be stationary dedicated repeaters, APs, or limited mobility ARSs [3]. Choosing these devices implies considerable infrastructure, administration, and maintenance cost but a more reliable and secure service can be provided.

User-owned devices can be stationary wireless enabled desktops, wireless routers, or MTs. Choosing these devices allows high flexibility at no extra infrastructure cost, but reliability and security diminishes especially when MTs are used because the link failure due to users' mobility and/or battery drainage becomes more frequent and the relaying host may not be trustful.

To decide which types of relaying devices to be used, the wireless network environment should be considered. In 3G, users are provided with a range of services with a wide range of data-rates. The traffic patterns are no longer solely proportional to the number of users in the cell. Users may have several ongoing connections, each corresponding to a different data-rate for different QoS classes. Such type of users can collectively cause hot spots anywhere, anytime. Carrier-owned relaying devices are inflexible to deal with hot spots, unless the traffic patterns and network topologies are known a priori. An alternative solution is to utilize user-owned devices such as MTs. In fact, most MCN proposals, such as ODMA [1], A-Cell [11], AMC [12], and PARCelS [9] assume MTs as relaying devices.

Carrier-owned relaying devices and user-owned delaying devices may co-exist. The former can be used to serve the areas where traffic patterns and network topologies are known a priori and/or predictable. Using these devices allows high reliability, which is important for "always on" service provisioning. The latter could be used for dynamic load network environment, unexpected high call demand emergency situation, and/or non-delay sensitive service. In fact, user-owned wireless stationary (wall-plugged) devices have great potential because they are more reliable in terms of energy supply and availability. Indeed, many such devices are readily available in cities and residential areas.

Note that when user-owned relaying devices are used, incentive schemes are needed to encourage users to offer signal-relaying service. Incentives could be in form of monetary rewards, service level upgrades, and extra bandwidth provisioning. Methods of charging and rewarding for relaying services may also be needed. Charging methods could be based on packet size and the number of relaying hops involved. Rewarding methods could be based on an end-to-end basis or hop-by-hop basis. More discussions on these topics are in Ref. [14].

3.4. Wireless interface

In MCNs, there are basically two types of communications: cellular and relay. The cellular communications are between the BS and a mobile node or a relaying device. The relay communications are between relay stations, or a MT and a relaying station. To provide these communications, a mobile device may be equipped with a single- or dual-wireless interface. Dual-interface requires two frequency bands, one for cellular access and the other for relay access. The trade-off is between cost and complexity. Using a single-interface has no equipment cost impact, but signals for relaying cause interference to the cellular access. Using dual-interface reduces system complexity and avoids interference from the relaying component, but equipment cost increases and two frequency bands are required. Sometimes, an extra frequency band may not be available. If free ISM bands are used, interference issue due to other ISM bands users exist. Both choices are commonly used in MCN proposals.

3.5. Communication mode

In Ref. [8,10,15–17], peer-to-peer (P2P) communications mode were suggested to help reducing the load of a cell. P2P mode of mobile nodes allows mobile nodes to communicate with other mobile nodes without going through the BSs. The trade-off is an increase in the complexity of the system. This mode is useful for source node and destination node, which are not too far away from each other in terms of number of hops. Although not many MCN proposals have this feature, it could easily be added by slightly modify existing routing schemes.

3.6. Supporting technology

Supporting technologies, such as directional antennas and GPS, are assumed in some recent MCN proposals. Directional antennas help reduce interference and power consumption, increase spatial (channel) reuse, and decouple multipath routes. GPS provides location information of mobile nodes, which helps reduce routing overhead for obtaining the network topology information. Both technologies pose extra cost to the MTs. Directional antenna technology for MT is still in development stage whereas GPS technology is mature and has become popular.

Directional antenna technology for MT has been an active research area. In Ref. [18], a lower power consumption small size smart antenna, called electronically steerable parasitic array radiator (ESPAR), was proposed. In Ref. [19], a reduced-size design of ESPAR, called dielectric embedded ESPAR (DE-ESPAR) is proposed. Testing results show that DE-ESPAR achieves a maximum gain of 5.1 dBi. Recently, the performance of a 7-element ESPAR antenna for mobile phone and WLANs is studied in Ref. [20]. Numerical results show that the performance is satisfactory.

3.7. Routing

Routing is one major issue in MCNs because it affects packet delay, and system throughput. When designing a routing protocol, the control strategy and path selection metric need to be decided.

3.7.1. Control strategy.

As MCNs contain co-ordinators (BSs or APs) and MTs, routing control may be centralized, de-centralized, or hybrid. In centralized routing, BSs are responsible for route discovery and maintenance. This utilizes their unlimited power supply and high computational power. It also helps avoid consuming the precious battery power of mobile nodes for route information exchange and route computation. For example, in CAHAN [8], a central controller periodically receives the location information from each MT in the cell to determine the route of the *ad hoc* subnet (cluster) heads with which MTs communicate. Centralized routing is especially useful in the situation where the cell size is flexible that was explained previously in Section 3.2. However, when mobiles are outside of the maximum transmission range of a BS or an AP, a decentralized (distributed) routing scheme, such as dynamic source routing (DSR), is desirable. Some MCN proposals employ distributed routing (relaying) schemes. For example, in mobile-assisted data forwarding (MADF) [21], mobile nodes which are willing to relay data packets may declare themselves as forwarding agents (relaying nodes) based on their local traffic condition. If the traffic is less than a certain threshold, they broadcast a message to their neighboring mobile nodes indicating that they have available channels for relaying data packets. Then, a mobile node in a congested cell chooses a relaying node to relay its data packets to a less congested neighboring cell based on the link quality between itself and the relaying node and estimated packet delay.

In MCNs, a hybrid routing approach is commonly used. Route control is shared by the BS and mobile nodes. For example, in cellular base routing (CBR) [17] of hierarchical multi-hop cellular network (HMCN) [17] and cellular based source routing (CBSR) [22] of cellular-based multi-hop network (CBM) [22], mobile nodes collect neighborhood information and send it to the BS for route computation.

This helps reduce the route computation overhead at relaying nodes. In addition, not only source node can initiate a relaying request, a relaying node (or forwarding agent) can also take the initiative by advertising their free channels (available capacity) for relaying [15,17,21]. Hence, routing overhead is shared amongst source nodes and relaying nodes.

3.7.2. Path selection metric.

Different MCN proposals have different path selection metrics. Metrics include BS reachability, hop count, path loss, link quality, signal strength, bit error rate (BER), carrier-to-interference ratio (C/I), delay-sensitivity, throughput, power, battery level, mobile speed, and energy consumption. With BS reachability information provided by relaying nodes, mobile nodes can select the best next hop-relaying node to reach the BS. Imposing a hop count limit helps bound the packet delay, but reduces the chance of obtaining relaying paths, and, hence, the reachability. Finding optimal hop count values for MCNs is still an open research area. Choosing paths based on the smallest number of hops also raises fairness and energy efficiency issues. Base-centric routing (BCR) [23] of MCN-p [10] is an example. Link quality may be expressed as a function of path loss, signal strength, BER, and C/I. Delay and throughput are common metric because they reflect the network performance directly. Minimum power routing is important in CDMA-based MCNs to reduce interference to achieve high-cell capacity. Battery level, mobile speed, energy consumption are useful for assuring the reliability of no-going relaying paths. Other possible metrics include traffic load, mean queue length, and number of packets queued along the path.

3.8. Channel assignment

In MCNs, channel assignment for dedicated forwarding, inter-cell and nodal may be involved.

3.8.1. Dedicated forwarding channel.

Some MCN proposals such as MADF [21] set aside some dedicated channels for packet forwarding. This helps avoid interfering the channels for cellular communications. However, it raises the question of how many channels or which channels should be set-aside. Improper channel assignment increases the chance of channel idling and, hence, wasting radio resource. To maximize the radio resource utilization, an effective dynamic channel assignment scheme for MCNs is needed.

3.8.2. Intercell and nodal channel assignment.

In cellular networks, channel assignment usually deals with assigning channels (frequencies) to neighboring cells to maximize channel reuse. Each cell is assigned a number of channels which are different from those assigned to its adjacent cells to avoid interference. Each cell is a discrete entity and is assumed not exchange wireless signals with its adjacent cells. Each MT communicates with its own BS. We call this *inter-cell* channel assignment. An example of inter-cell channel assignment scheme is in [24]. In MCNs, each MT interacts with its neighboring MTs for relaying purposes. Hence, channel assignment is required for each node. We call this *nodal* channel assignment. Examples of nodal channel assignment schemes are in Ref. [25,26]

The choice of wireless technology influences the decision of whether inter-cell or nodal channel assignment is needed. If WLAN technology is used, only inter-cell channel assignment is needed. MCN-p [10] and multi-hop cellular network with reduction of BSs (MCN-b) [10] are in this category. If wireless technology, such as 2G, 3G, or WiMAX, is used, nodal channel assignment and/or inter-cell channel assignment is needed. A-Cell [11] and AMC [12] are in this category. Improper channel assignment would greatly reduce channel reuse, increase the chance of signal collisions, packet delay, and reduce the system throughput. In Section 4.5, we discuss an optimal nodal channel assignment scheme which is recently proposed to address these issues.

3.9. Load balancing

Load balancing in cellular networks helps alleviate the hot spot problem by relaying traffic load from congested cells to other less-congested cells to reduce call blocking and utilize the radio resource. In MCNs, load balancing not only involves balancing among cells, but also balancing among relaying nodes. It also involves the choice of relaying device.

iCAR [3] and PARCelS [9] are two schemes for load balancing among cells through *ad hoc* relaying. In iCAR, low cost limited mobility ARSs are placed in hot spot areas for traffic relaying. This strategy is not only costly, but also not flexible enough to handle the highly dynamic load situation in 3G networks. PARCelS uses mobile nodes for relaying. When a BS is congested, mobile nodes search best routes to other non-congested cells. Route information is forwarded to BSs for selection. This strategy requires considerable routing overhead and does not take advantage of the presence of powerful BSs. In addition, both schemes do not take into account the load balancing among MTs.

Balancing among MTs is important to avoid power over consumption of some relaying nodes such that these nodes are out of battery and affects the availability of route and connectivity. Although this issue is more related to routing, balancing load among cells and MTs is important to achieve good network performance. For example, when a load balancing process for BS is activated, which source nodes should be chosen for rerouting the traffic? A-Cell load balancing (ALBA) [13] scheme addresses this issue and is discussed in Section 4.6.

4. RESEARCH DIRECTIONS AND CHALLENGES

The success of MCNs hinges on their ability to provide connectivity solutions that have low cost, high capacity, large coverage, and QoS assurance. These criteria are influenced by the design decision factors. As cost is one important criterion that influences the decisions of service providers on the core wireless technology for MCN implementations, it would also influence the future research directions of MCNs as well.

Different service providers have different cost and strategic concerns and hence, different preferences. Existing service providers may prefer utilizing their existing 2G or 3G infrastructure instead of buying new technology and new infrastructure to minimize cost impact and investment risk. New service providers in this business may opt for WiMAX, which requires lower initial infrastructure cost and provides comparable features as 3G technology. WiMAX also allows the use of ISM bands. This factor eases the concern of new service providers on the availability and licensing of frequency spectrums. MCNs based on WLAN technology may have inconsistency performance due to the interference from other WLANs or other devices operating on free ISM bands. Nevertheless, a detailed cost and benefit analysis for each MCN design to meet individual service providers' need should be performed. In future, MCN architecture based on 2G, 3G, or WiMAX may co-exist and WLANs might be used as an augmented technology to MCNs. Regarding to recent MCN proposals and research activities, cellular-based MCNs, WiMAX-based, and combination (cellular with WLAN) are three major possible directions (see Figure 2). In fact, research works addressing some important issues of these types of MCNs have been conducted. These include capacity enhancement, energy consumption, cell size, routing, channel assignment, load balancing, and security. In the following section, we discuss these issues, and other technical challenges.

4.1. Capacity enhancement

Although capacity enhancement through multi-hop relaying in a CDMA system, *viz*. CDMA MCNs, is a well-accepted claim, the capacity gain in this system was not quantified until recently. The work in Ref. [27] derives equations to quantify resulting interference when using multi-hop communication in uplink transmissions. To model the CDMA, MCN environment, users, and calls are assumed uniformly distributed across the area of the network and each cell is represented (divided) as concentric circular regions centered at the BS. Only MTs inside innermost region are allowed to send their data directly to BS. MTs in outer region have to relay their signals through other MTs residing in next region closer to BS. MTs use fixed transmission power except in last hop to BS and power control is applied at BS and on all hops. Based on the equations, the authors derived an upper bound on number of supported users based on QoS (data rate and BER) requirements. The authors showed that capacity is increased in multi-hop case compared to a single-hop case in terms of either the number of supported calls or data rate. They also showed that, with power control, capacity increases even more. An observation was that extra relaying MTs result in higher intra-cell interference, but large reduction in inter-cell interference, decreasing the total resulting interference.

In Ref. [2], the authors extend their capacity analysis to include the effect of non-uniform distribution and network load. They showed that call distribution inside a cell does not affect the capacity of the cell itself in single-hop networks because of power control, but does affect the capacity of this cell in MCNs because the position of the call inside the cell determines the number of hops needed to reach BS. When a call is near cell borders, more hops are needed resulting in more interference, decreasing the capacity of the cell. When all calls in one cell tend to originate near the borders, the capacity of all adjacent cells decreases significantly in single-hop networks, but remains nearly the same in MCNs. Hence, multi-hop communication is more advantageous for border calls.

For CDMA-based MCNs with WLAN technology as the relaying interface, the authors in Ref. [28] showed that significant throughput gain can be achieved through multi-hop relaying in these networks. In their system model, each MT has two interfaces: cellular interface for communicating with BS using cellular frequency band and relaying interface for relaying purpose using ISM bands. The authors focus on studying the capacity enhancement on the cellular interface assuming that the relaying (WLAN) interface has a much higher data-rate than that of the cellular interface and is not a concern. The formula for the signal-to-interference-and-noise ratio (SINR) at each active mobile node in each cell is derived. SINR is constrained by the required SINR threshold to achieve a desired BER. The minimum power of each BS is computed. Based on the formulation, the feasibility of the increase of its transmission rate of each active mobile is checked. If the increase in power satisfies the transmission power constraint, the transmission rate is increased. The iterating procedure continues until no more transmission rate can be increased. The study focuses on a two-hop relaying system in which the coverage extension of system may be limited. The performance of the system using more hops for relaying is still an open issue.

For WiMAX-based or OFDMA-based multi-hop relay networks, the authors in Ref. [29] showed that significant capacity gain is achieved by providing enough relays to create line of sight relaying paths in a macrocell environment. The authors showed different network throughput for various cell sizes and number of relaying hops. In Ref. [30], the authors analyzed the achievable rate in a co-operative cellular network, a MCN in which providing more than one relaying path for a source node are provided.

4.2. Energy consumption reduction

MTs usually rely on batteries for their energy supply. In order to keep these batteries last longer, energy consumption has to be reduced. Multi-hop communication promises savings in energy consumption. Ref. [31] quantifies the energy consumption in multi-hop CDMA networks. The results show that reduction in energy consumption in these networks is possible using multi-hop communication compared to that in single-hop CDMA cellular networks. The authors also showed that power control saves more energy and is more rewarding with a small number of hops. The effects of network environment were also studied. It was shown that multi-hop communication results in more reduction in energy consumption in high path loss environments. The authors emphasized the fact that the consumed energy decreases with increasing the number of hops until a certain point, then it increases again. This happens when the reduction in consumed energy for transmission is suppressed by the increase in consumed energy for electronics operation because of a large number of hops for each call. This shows that for each network there is an optimum number of hops to minimize energy consumption, based on network environment and MTs hardware.

A similar analysis of energy (power) consumption for these networks is performed in Ref. [32] except that a two-hop relay is considered. For OFDMA-based multi-hop co-operative relay networks, the authors in Ref. [30] showed that the average power consumption of using two parallel relays between a source node and the BS is less than using one relay.

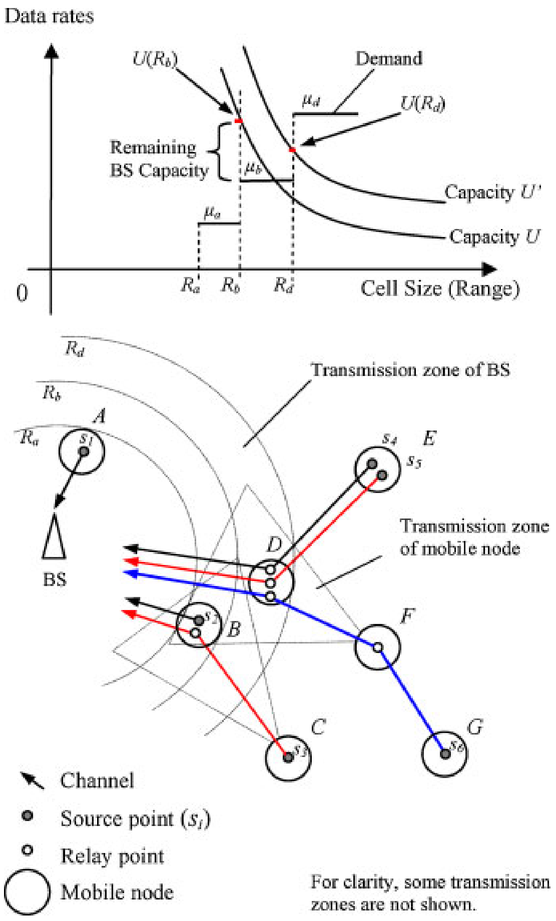


Fig. 3. Capacity-demand model and network model for AMC and OCA.

4.3. Adaptive cell size approach

A study showed that multi-hop relaying enlarges the area of coverage and increases the throughput in a CDMA-based MCN [33]. However, the effect of cell size on system throughput has not been exploited until recently.

As mentioned in Section 3.2, AMC [12] is the first MCN architecture addressing the cell size issue in time division duplex (TDD) CDMA MCN environment. AMC uses an adaptive cell size approach. Given a network topology, a traffic pattern, and the cell capacity function of a TDD wide-band CDMA (W-CDMA) MCN, AMC dynamically adjusts the cell size to an optimal value to balance between network reachability and cell capacity to maximize the throughput and available cell capacity. The scheme is modeled as a capacity-demand model.

- The *Capacity* represents the cell capacity function which is a continuous *decreasing* function over the cell size.
- The *Demand* represents the total demand of the source nodes and is an *increasing* function over the cell size.

Figure 3 illustrates an example of applying this model to a MCN scenario. In the figure, a session (connection or call) initiated in a source node is represented by a source point s_i which requires a certain amount of capacity (demand). One or more source points can be associated with the same mobile node for different connections for different services, such as a voice call or file downloading. The connection is relayed through a relaying point in some intermediate relaying nodes to the BS. A mobile node can be a source node, relaying node, or both. A call is covered by a cell if the last hop node on the relaying path is within the range of the cell. For example, nodes *A*, *B*, and *D* are last hop nodes. Thus, the cell size determines whether these nodes and, hence, the calls are covered by the cell or not. Mobile nodes are assumed equipped with directional antenna and GPS. In the figure, μ_a represents the cumulated demands of node *A* in the range of R_a. μ_b represents the cumulated demands of source nodes *A*, *B*, and *C* having their last hop nodes *A* and *B* within the range of R_b, and so on.

Two different cell capacity curves *U* and *U*’ are used to illustrate two typical optimal cell size cases. For the first case, the capacity curve *U* intersects the demand curve. The optimal cell size is R_b which represents the choice that maximizes the data rate, that can be served, and the remaining BS capacity. In the example, the cell capacity is

$U(R_b)$ and the maximum demand that can be served is μ_b. Thus, the remaining cell capacity $= U(R_b) - \mu_b$, which is also maximized. Note that choosing the cell size beyond R_b would reduce the remaining available cell capacity and, in the worst case, would cause insufficient cell capacity to fulfill the demands μ_b.

For the second case, the capacity curve U' does not intersect the demand curve. The optimal cell size occurs at either R_b or R_d. If the cell capacity for the range R_d satisfies at least one of the demands of source points s_4, s_5, and s_6 relayed or requested through node D at R_d, the optimal cell size is at R_d; otherwise, the optimal cell size is at R_b. The authors formulated this decision problem as a knapsack problem which is to choose as much items as possible (each having a possibly different value) that can fit into one bag to achieve a maximum value. In this case, the items are the calls, each having a demand, whereas the bag is the cell capacity at R_d. It is shown that an adaptive cell size approach has on average 17% improvement on cell throughput over a predetermined cell size approach. An optimal cell size solution for a multiple-cell case can be found in Ref. [34].

4.4. Flexible cell size routing

Most routing protocols or strategies for MCNs use hybrid control to take the advantage of the powerful BS. However, none of the proposals (ACAR [13] being the exception) take the cell size into consideration to increase the effectiveness and efficiency of routing.

ACAR [13] is an on-demand load-aware routing scheme specifically designed for 3G MCNs. Like most routing protocols, it has routing discovery and route maintenance. The idea of ACAR is to take advantage of the cell capacity *versus* cell coverage characteristic, *viz.* the cell breathing effect, of a CDMA cellular system. Route discovery or route maintenance is done in a single-hop long range (low data-rate) transmission while data communication is done in multi-hop short range (high-data rate) transmissions. This helps reduce routing overhead while retaining the benefits of using multihopping. If no multi-hop short-range path is available for data communications, a single-hop long-range may be used if cell capacity permits. In this case, no potential call requests, which are within the maximum transmission range of a BS, will be denied. If MTs are outside of the maximum transmission range of the BS, *ad hoc* network routing protocol such as DSR is assumed.

ACAR uses several metrics including battery level, loading conditions, and speed and energy consumption, to select mobile nodes for relaying. This increases the reliability of the relaying paths. A mobile node is chosen as a relaying node if its energy consumption, speed, and loading do not exceed predefined thresholds and the battery level is above a battery level threshold. Once reliable nodes are identified, a shortest path within a preset hop-count is computed. The path is further refined (replacing the last hop node of a relaying path by the second last hop node) to reduce the relaying delay if the cell capacity is enough.

ACAR [13] fits well with the adaptive cell size architecture such as AMC [12] and is suitable for sparse and dense network situations. However, performance comparison with other routing protocols is still pending.

4.5. Minimum delay channel assignment

In general, the purpose of channel assignment in cellular networks or MCNs is to increase or maximize channel reuse [24,25,35] whereas a routing scheme handles the packet delay issue in MCNs. But, channel assignment also has a great impact on packet delay. There is no optimal solution for minimizing delay in MCN prior to the recent result on optimal channel assignment (OCA) [26]. OCA is a nodal channel assignment approach (see Section 3.8) and was proposed to minimize the packet delay while avoiding signal collisions, channel conflicts, and time-slot conflicts in TDD CDMA MCNs.

The network scenario in Figure 3 is used to illustrate this scheme. To avoid signal collisions, when a relaying node receives signals from more than one transmitting node, the channels assigned to the transmitting nodes must be different; or when a receiving node is within the transmission zone of another transmitting node, its receiving channels must be different from the transmitting channels of the other node. For example, nodes D and B fall into these situations, respectively. To avoid channel conflicts, when a source node or relay node serves several connections, the channels assigned to them must be different. For example, channels assigned for source points s_4 and s_5 have to be different. Time-slot conflict occurs when two consecutive nodes on a relaying path are assigned with channels having the same time-slot. In this case, signals cannot be received at the receiving node since a mobile node cannot receive and transmit signal at the same time on the same frequency. For example, nodes E and D are a consecutive node pair.

When a packet arrives in a relaying node, the packet has to wait until its time-slot on the relaying node to be transmitted. In an ideal situation, the packet is sent out in an immediate time-slot after it has been received. However, the condition usually cannot be achieved because of avoiding signal collisions, channel, and time-slot conflicts.

The scheme is formulated as an integer programming problem. Given a set of paths, each path has a source point and relaying points, each source point or relaying point is assigned exactly one channel. A channel is defined as a timeslot and code pair. To model this condition, every possible time-slot and code is represented as a binary variable $\{0, 1\}$. The sum of the values of all time-slot variables for a channel assigned to a vertex is restricted to 1. Code variables are treated in the same way. These conditions enforce exactly one time-slot and one code assigned to the vertex. For example, if time-slot t is selected, the variable representing t is set to "1" whereas all other time-slot variables need to be zero. To enforce no channel conflicts, the summation of the values of the time-slot variables and the code variables of two conflicting vertices is restricted to be less than or equal to 3. That is, their time-slots and/or codes are different. To enforce no time-slot conflicts, the summation of the values of the time-slot variables of two conflicting vertices is restricted to be less than or equal to 1. The objective function of OCA is to minimize the total sum of all the time-slot waiting time of every consecutive node pair of vertices on every relaying path.

Although minimum delay is achieved, more work is needed to incorporate this scheme into a QoS framework. Also, OCA is computationally expensive and might not be suitable for large-scale real-time problems.

4.6. Best effort load balancing

As mentioned in Section 3.9, the ARSs in iCAR [3] is still costly and not flexible enough to handle the highly dynamic load situation in 3G networks whereas PARCelS [9] does not take advantage of the presence of powerful BSs for reducing routing overhead. In both schemes, the priorities of mobile nodes for load migration are not considered which could affect the QoS provisioning for the nodes.

ALBA [13] is a dynamic load balancing scheme for CDMA MCNs which considers the location and priority of mobile nodes for load migration. The basic idea is to shift traffic load from a highly loaded cell to slightly loaded cells in a best effort manner. Best effort is assumed because relaying routes for load migration may not exist especially in a highly dynamic-load network, *viz.* 3G systems. ALBA may be also applied to any heterogeneous load environment.

ALBA periodically checks the load status of the cells in the network. If cell load deviation is greater than a global load deviation threshold, ALBA starts load migration planning. ALBA selects a target cell and a source cell. The target cell is the least load cell in the network. The source cell is a neighboring cell of the target cell and has the highest load above the load of the target cell. To proceed further, the load deviation between the source cell and the target cell needs to be greater than a neighbor load deviation threshold and the call blocking ratio of the source cell also needs to be greater than or equal to that of the target cell; otherwise, no load will be migrated. Then, ALBA selects a source point (connection) of a source node from the source cell based on the migration priority of the connection, which is a function of the QoS class of the connection and the distance between the source node and the BS of target cell. A connection with lower QoS class level or the source node has shorter distance towards the target BS has a higher priority. The former strategy helps minimize the disruption to on-going connections having higher QoS level. The latter strategy helps reduce the transmission distance and, thus, lower the interference. Once a source point is selected, ALBA calls a routing and channel assignment mechanisms to find a route with channel assigned for relaying. Whether the finding of the route is a success or not, ALBA continues to select other source points for load migration until the load of the source cell is not greater than the load of the target cell or all source nodes in the source cell are tried.

After load migration is a success between the two cells, ALBA reviews the new load distribution of the network. If the network load deviation is still greater than the global load deviation threshold, ALBA selects another set of target cell and source cell for load migration. These procedures continue until the network load deviation is less than the global load deviation threshold or no further load migrations can be done, i.e., all cells are tried. Then, ALBA sends signals to the corresponding BSs and MTs for updating the channel assignment and routing tables.

Although simulation results shown that ALBA has good performance in terms of throughput and lower call blocking ratio, like most load balancing schemes, ALBA is a heuristic. A universal optimal load-balancing scheme for MCNs remains an open problem.

4.7. Security

Like *ad hoc* networks, the security issues in MCNs are important, including secure routing, authentication of users, and security in charging and rewarding schemes for packet forwarding. Unlike *ad hoc* networks, however, MCNs have a centralized authority for registration and auditing process. This gives MCN better ability in preventing and detecting security attacks. In Ref. [36], a secure macro-/micromobility protocol was proposed to prevent various security treats, such as Forged BS, unauthorized network access, registration attacks (registration poisoning, bogus registration, and registering replay attack), multi-hop paging/routing cache poisoning, and multi-hop routing attacks (anti-integrity, impersonations, anti-confidentiality, and duplications). The idea is based on registration and certificate-based authentication. As co-operation in packet forwarding is important for these networks to be successful, various charging and rewarding schemes [37–41] have been proposed to encourage users to co-operate in packet forwarding. The issues of selfish nodes, which refuse to pay and/or cheat to obtain reward or free packet delivery services, and fault accusation of honest nodes of misbehavior are also discussed. In general, protocols are designed based on lightweight cryptographic techniques, such as symmetric key systems instead of the heavily-weight public key system to avoid high computational overhead. This is especially important in MCN where mobile devices are resource constrained.

4.8. Quality of service

Quality of service in MCNs is still a major open topic of study as so far most works focus on the capacity, BER, or delay issues. Other performance metrics such as fairness, delay jitter, aggregate, and per-node throughput and packet loss ratios also needs to be considered.

For OFDMA-based MCN, in Ref. [42], the authors proposed a transmission scheme selection algorithm which selects the best transmission scheme for different conditions based on the QoS requirements and location of MTs and the channel conditions. Simulation results showed that the transmission selection schemes achieve better utilization of subcarriers. However, only two-hop relaying is considered. For CDMA-based MCN, in Ref. [43], the authors propose a rate adaptation and power adjustment scheme to provide QoS for connections (calls) of different QoS classes based on their QoS requirement and interference to determine the achievable data-rate and BER. The data-rate for a call having lower priority may be degraded so that the QoS requirement of a call having a higher priority can be maintained. For a WLAN-based MCN, the authors in Ref.[44] proposed a reduced congestion queuing scheme to reduce congestion of packets to support the QoS of service in terms of packet delay. The idea is to give higher priority for the packets which are generated at distant nodes than the relaying nodes closer to the BS on a relaying path.

4.9. Other challenges

Although some major issues of MCNs have been already addressed, a comprehensive framework for MCNs is yet to be developed. In addition, other issues, such as power control, user mobility, and handoff, are still open problems.

Power control adjusts the transmission power of the BS and mobile nodes. It helps enhance capacity and minimize power consumption of mobile nodes. The performance gain with power control in CDMA MCNs was quantified as explained previously. Power and rate control algorithms were proposed for CDMA-based with WLAN relaying interface MCNs in Ref. [28]. However, in the work, only two-hop relaying is considered. Power control for multi-hop relaying in these networks, that exceeds two hops, remains an open problem.

High user mobility increases the likelihood of link failure and handoff, resulting in frequent route update and reassignment of channels. A large cell size helps alleviate this problem, but reduces the cell capacity. Assessing the interdependence of cell size, capacity, mobility and handoff is a challenge.

5. CONCLUSIONS

MCNs are considered as a promising next generation wireless architecture. This paper was motivated by the fact that in order to achieve wide deployment of such networks, the design factors for MCNs need to be identified and their effect needs to be studied. Design decision factors discussed in the paper are wireless technology, cell size, relaying device, wireless interface, communication mode, supporting technology, routing strategy, channel assignment, and load balancing. We believe these factors to be closely interrelated and to highly affect other criteria such as cost, capacity, coverage, and QoS. Proper design decisions are crucial for the success of MCNs. This paper presents a detailed analysis of such design decision factors for MCNs. Classifications of most existing MCN proposals are provided. Future research directions, issues related to capacity and energy consumption, innovative approaches including adaptive cell size, flexible cell size routing, minimum delay channel assignment, and best effort load balancing, security, and remaining challenges are discussed.

MCN architecture, such as AMC, having an adaptive cell size feature and using user-owned device for relaying and a single air interface, has benefits in terms of capacity, coverage, flexibility, adaptability, QoS assurance, and applicability to recent cellular technology. No extra infrastructure cost is required. The trade-off is that it introduces complexity in channel assignment and power control (for cell size adjustment). A simpler design is to use WLAN technology for the relaying component while the cellular component remains. *Ad hoc* global system for mobile communications (A-GSM) [15] is an example of this design. In this case, no new channel assignment or medium access scheme is needed to develop for the relaying component. The trade-off is that QoS is not easy to assure because the interference from other ISM band devices may not be known. In addition, the cell capacity is not optimized as compared to that of AMC. If carrier-owned relay stations, such as the ARSs in iCAR, are used, additional infrastructure cost is required. The cheapest and simplest design is based on WLAN technology. MCN-p is an example of this design. AP is cheap and no channel assignment is required. The trade-off is that this architecture relies on high node density to achieve connectivity. However, in practice, high node density may not always be the case. In addition, QoS assurance is still an open issue, especially when high quality voice communications is required, because cellular infrastructure is not available.

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Appendix: List of Acronyms

A-Cell	*Ad hoc* cellular
A-GSM	*Ad hoc* global system for mobile communications
AMC	Adaptive multi-hop cellular
AP	Access point
ALBA	A-Cell load balancing
ACAR	A-Cell adaptive routing
ARS	*Ad hoc* relaying station
BER	Bit error rate
BS	Base station
C/I	Carrier-to-interference ratio
CAMA	cellular aided mobile *ad hoc* network
CAHAN	Cellular *ad hoc* augmented network
CBM	Cellular based multi-hop
CBR	Cellular base routing

CBSR	Cellular based source routing
CDMA	Code division multiple access
DSR	Dynamic source routing
D. Ant.	Directional antennas
OFDMA	Orthogonal frequency division multiple access
GPS	Global positioning system
HMCN	Hierarchical multi-hop cellular network
HWN	Hybrid wireless network
iCAR	Integrated cellular and *ad hoc* relay
ISM	Industrial scientific and medical
LDPR	Location-dependent packet relay
MADF	Mobile-assisted data forwarding
MCN	Multi-hop cellular network
MCN-b	Multi-hop cellular network - reduction of BSs
MCN-p	Multi-hop cellular network - reduction of power
MRAC	Multi-hop radio access cellular
MT	Mobile terminal
OCA	Optimal channel assignment
ODMA	Opportunity-driven multiple access
P2P	Peer-to-peer
PSTN	Public switching telephone networks
QoS	Quality of service
PARCelS	Pervasive *ad hoc* relaying for cellular systems
SINR	Signal-to-interference-and-noise radio
SOPRANO	Self-organizing packet radio *ad hoc* networks with overlay
TDD	Time division duplex
TDMA	Time division multiple access
UCAN	Unified cellular and *ad hoc* network
VCN	Virtual cellular networks
W-CDMA	Wideband code division multiple access
WiMAX	Worldwide interoperability for microwave access
WLAN	Wireless local area network

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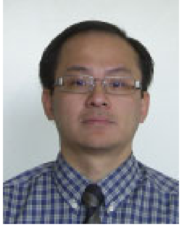
Authors' Biographies



Y. Hung Tam received his B.Sc. in Computer Science from Trent University, Canada, in 2002, and his M.Sc. and Ph.D. in Computer Science from Queen's University, Canada, in 2004 and 2009, respectively. He has authored a number of papers in international journals and conferences in the area of wireless communications and networks. His research interests are in radio resource management in wireless and mobile networks, especially in channel assignment, capacity and coverage management, and load balancing in multi-hop cellular, cellular and ad hoc networks. He is a member of the IEEE. He is a recipient of the Best Paper Award of the IEEE GLOBECOM in 2007.

Hossam Hassanein is with the School of Computing at Queen's University working in the areas of broadband, wireless and variable topology networks architecture, protocols, control and performance evaluation. Dr. Hassanein obtained his Ph.D. in Computing Science from the University of Alberta in 1990. He is the founder and director of the Telecommunication Research (TR) Lab www.cs.queensu.ca/∼trl in the School of Computing at Queen's. Dr. Hassanein has more than 350 publications in reputable journals, conferences and workshops in the areas of computer networks and performance evaluation. He has delivered several plenary talks and tutorials at key international venues, including Unconventional Computing 2007, IEEE ICC 2008, IEEE CCNC 2009, IEEE GCC 2009, IEEE GIIS 2009, ACM MSWiM 2009 and IEEE Globecom 2009. Dr. Hassanein has organized and served on the program committee of numerous international conferences and workshops. He also serves on the editorial board of a number of International Journals. He is a senior member of the IEEE, and is currently chair of the IEEE Communication Society Technical Committee on Ad hoc and Sensor Networks (TC AHSN). Dr. Hassanein is the recipient of Communications and Information Technology Ontario (CITO) Champions of Innovation Research award in 2003. He received several best paper awards, including at IEEE Wireless Communications and Network (2007), IEEE Global Communication Conference (2007), IEEE International Symposium on Computers and Communications (2009), IEEE Local Computer Networks Conference (2009) and ACM Wireless Communication and Mobile Computing (2010). Dr. Hassanein is an IEEE Communications Society Distinguished Lecturer.

Selim G. Akl received his Ph.D. degree from McGill University in Montreal in 1978. He is a Professor of Computing at Queen's University, Kingston, Ontario, Canada, where he currently serves as Director of the Queen's School of Computing. Dr. Akl's research interests are in parallel and unconventional computation. He is author of *Parallel Sorting Algorithms* (Academic Press, 1985), *The Design and Analysis of Parallel Algorithms* (Prentice Hall, 1989), and *Parallel Computation: Models and Methods* (Prentice Hall, 1997), and a co-author of *Parallel Computational Geometry* (Prentice Hall, 1992) and *Adaptive Cryptographic Access Control* (Springer, 2010). Dr. Akl is editor in chief of *Parallel Processing Letters* and presently serves on the editorial boards of *Computational Geometry*, the *International Journal of Parallel, Emergent, and Distributed Systems*, and the *International Journal of High Performance Computing and Networking*.

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