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Multihop cellular networks: Technology and economics

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A B S T R A C T

Recently, multihop cellular networks (MCNs) were proposed to preserve the advantages of traditional single-hop cellular networks with multihop ad hoc relaying networks, while minimizing the drawbacks that they involved. In this way, MCNs enhance the performance of both the existing cellular networks and ad hoc networks. Consequently, MCN-type system is considered as a promising candidate of fourth generation (4G) wireless network for future mobile communications. This paper surveys a number of MCN-type architectures in literature through a comprehensive comparison and discussion among the proposed architectures. The discussion is divided into two phases. In the first phase, we review the concept of MCN and compare the selected MCN-type architectures from a technology perspective. In the second phase, we further compare and discuss the economic perspective on the deployment of MCNs. Specifically, we focus on the economic considerations for deploying relays in MCN-type systems.

1. Introduction

The last decade has seen an unprecedented growth in mobile communications, fueled by an increasing demand for personal mobility in communications and advances in CMOS technology that allows light and handheld devices with long operating hours to be implemented with low cost. According to a recent study, the number of mobile subscribers worldwide will continue to rise to 3.96 billion, or approximately half of the world's population by the year 2011 [1]. Nowadays, many newer mobile phones are also integrated with functionalities including FM radio, digital camera, and MP3 player. Consequently, the services supported by mobile communications have expanded from simple voice to multimedia such as video conferencing and mobile gaming. These new services require a higher quality of service (QoS) as well as greater data rate. Furthermore, with mobile access to the Internet, the increasing growth in data traffic will further drive the need for higher bandwidth. Current infrastructures that support mainly voice traffic are facing a great challenge in meeting both the bandwidth and QoS demands of future mobile communication users.

For mobile communications, one paradigm with successful development is traditional single-hop cellular systems where a mobile station (MS) communicates directly with a base station (BS) [2]. The success of second generation (2G) cellular networks and the market deployment of the latest 3rd generation (3G) networks demonstrated the popularity of traditional cellular systems. Another paradigm of mobile communications is multihop ad hoc networks [3], which are infrastructureless, self-organizing and rapidly deployable without any site planning, unlike traditional cellular networks. For a multihop ad hoc network comprised solely of mobile users (also known as mobile ad hoc networks or MANETs), every node can play the role of an intermediary station that relays packets of other nodes towards their destinations that otherwise cannot be reached using a single-hop transmission. The existing real-world MANETs are mostly deployed based on the ad hoc

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mode of IEEE 802.11 standard for wireless local area networks (WLAN), which can provide a high data rate of 54 Mbps for internet access and multimedia applications.

Both traditional single-hop cellular networks (SCNs) and MANETs have their respective advantages and drawbacks. The SCNs have reliable performance and mature technology support. However, its infrastructure is costly to build and it may still suffer from problems such as dead spots due to bad channel conditions or hot spots due to high communication traffic during peak hours. In addition, SCNs have several limitations related to the channel data rate, system capacity and network expansion. The channel data rate may not be enough for hot-spot areas where the number of MSs per area is much higher than that of the network specification. To address these limitations, additional spectra may be assigned or more BSs could be deployed for congested areas, which are the straightforward but inevitably costly measures. On the other hand, MANETs are cheap to deploy mainly due to the use of unlicensed spectrum of IEEE 802.11. However, the lower cost comes with less reliable performance as the channel contention and interference between nodes are more difficult to predict or control, and the multihop paths between source–destination are more vulnerable to the node mobility and node failure. The limitations of each network type in the above when operating standalone, led researchers to investigate a hybrid system that combines the benefits of single-hop cellular and multihop ad hoc relay networks, while avoiding their respective drawbacks [4].

In this paper, we survey the state-of-the-art technology of multihop cellular networks (MCNs) and related economics. The remainder of this paper is organized as follows. Section 2 revisits the concepts of MCN, highlighting the differences between MCNs and traditional SCNs, and the benefits we may gain from their deployment. Section 3 reviews the proposed MCN architectures in literature and Section 4 makes a comparison between these architectures in detail. In Section 5, we further discuss the issues involved in deploying (or selecting) relay stations in MCNs from an economic point of view. Finally, Section 6 concludes the paper.

2. Multihop cellular networks: Pros and cons

The concept of MCN was first proposed by Lin and Hsu [5] as an architecture that would preserve the benefits of traditional SCNs with infrastructure, while incorporating the flexibility of ad hoc networking. For clarity hereafter in this paper, we would refer to MCN as a general networking paradigm that integrates traditional SCNs and ad hoc networks by means of multihop transmission, unless we specifically refer to the MCN architectures proposed in [5].

Single-hop communication and multihop communication differ as follows. For a pair of communication entities, when the source node can reach its destination node directly, we refer to this type of communication scenario as single-hop communication. Similarly, multihop communication refer to the scenario where the source node can reach its destination node through only two or more single-hop communication links, where each intermediary node lying on the path between the source node and destination node would play the role of a relaying station. The fundamental idea of multihop communication is to break an original long communication link into two or more shorter links, and thus could reduce the required transmission power of each node participating in the communication scenario. Apparently, the reduced transmission power could also lead to a lower interference level and shorter frequency reuse distance. In addition, the need for short-range transmission in MCNs opens the possibility of using other higher data rate wireless technologies such as IEEE 802.11, Bluetooth, or Ultra-Wideband (UWB), in conjunction with the cellular technology.

For single-hop communication, one typical system is the traditional cellular systems where a MS will communicate with its nearest BS (or the BS with strongest signal strength for this MS) through a single hop to make a call to another MS. Thus, they may also be known as single-hop cellular systems. For example as shown in Fig. 1a, if both source node *A* and destination node *B* are in the same cell, the BS will forward *A*'s data to *B* through downlink transmission from the BS. Another example is that node *C* in cell *i* wants to communicate with node *D* in cell *j*. BS *i* will forward *C*'s data through the wired backbone link to BS *j*, which in turn will forward the data to *D* through the downlink transmission. For multihop communication in MCNs as shown in Fig. 1b, node *A* is allowed to communicate with node *B* directly without going through the BS and adopts the form of peer-to-peer communication like in the ad hoc networks. The traffic could also possibly be relayed by several MSs (or other relaying entities) over multiple hops before it eventually reaches the BS or the destination MS.

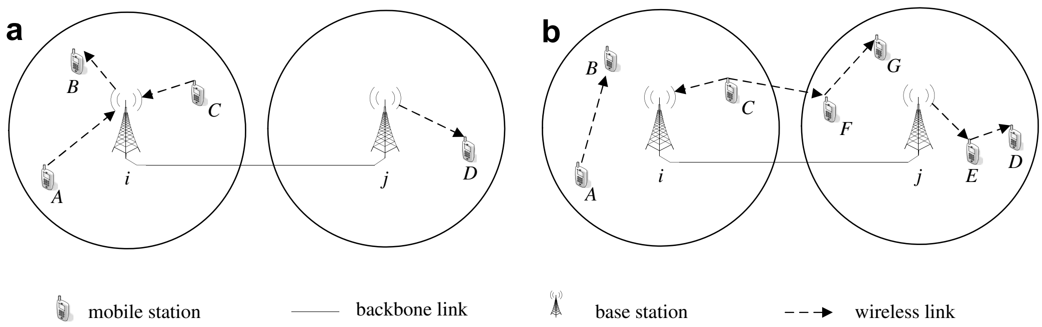

Fig. 1. (a) Single-hop cellular networks and (b) multihop cellular networks.

2.1. Benefits of MCNs

The advantages of MCNs over existing SCN-type architectures are summarized and described as follows:

- *Reduce total transmit power*: As shown in Fig. 2, we can compare the power level required using direct transmission and that using multihop transmission. Through simple estimation, the transmit power, $P_{\text{direct},A\to B}$, at MS A through direct transmission to MS B is given by

$$\begin{aligned} P_{\text{direct},A\to B} &= Kd_{AB}^{\gamma}P_r \\ &= K\left(\sqrt{d_{AC}^2 + d_{CB}^2 - 2d_{AC}d_{CB}\cos\theta}\right)^{\gamma}P_r \\ &> K(d_{AC}^{\gamma} + d_{CB}^{\gamma})P_r = P_{\text{relay},A\to C} + P_{\text{relay},C\to B}, \end{aligned} \tag{1}$$

  where K is the path loss constant, γ is the path loss exponent and P_r is the required received power for each receiving node. In (1), the inequality holds as long as θ is an obtuse angle. Thus, the $P_{\text{direct},A\to B}$ will be larger than the total transmit power, $P_{\text{relay},A\to C} + P_{\text{relay},C\to B}$, required from the two-hop transmission [5–12].
- *Increase system capacity*: Due to the reduced transmit power, the coverage of BS in MCNs becomes smaller than that in SCNs, and thus the spectra can be reused more frequently due to the shorter reuse distances. Consequently, the system capacity can be increased [5,7,10–14]. Similar to microcellular systems [15], as the coverage area decreases, the spectral efficiency increases. Thus, the capacity increases due to the additional number of available frequency channels per unit area.
- *Higher data rate services*: In the conventional CDMA cellular network, MSs near the BS will be able to enjoy high data rate services, while those far away from the BS will have to settle for low data rate services, due to power limitations. With MCNs, terminals far away from the BS will still be able to access high data rate services as their data can be relayed via other terminals that are closer to the BS [6,8,12,16]. Furthermore, when short range wireless technologies, such as IEEE 802.11, are used for such relaying, MSs can enjoy even higher data rate services.
- *Balancing traffic load*: Unbalanced traffic distribution will exacerbate the problem related to the management and allocation of limited capacity in traditional SCNs. In particular, some cells may still have enough available channels while other cells are heavily congested. Consequently, even though the traffic load has not reached the planned maximum capacity, a significant number of calls may be blocked or dropped due to the local saturation in congested cells. Assigning higher bandwidth to a congested cell, if possible, can increase the system capacity. However, this is not feasible under the current spectrum regulation. Moreover, it is not an efficient way to deal with the time-varying unbalanced traffic. In MCNs, multihop communication allows the traffic from congested cells to be diverted to other non-congested cells [17–19]. In this way, overall, call blocking probability of the entire network can be decreased by virtue of load balancing between the congested and neighboring non-congested cells. This also improves the spectrum efficiency.
- *Alleviate capacity bottleneck*: In MCNs, direct peer-to-peer communications are permitted and BS may not be involved in a communication process [5,11,13,17,20]. This alleviates the potential capacity bottleneck that can rise due to the limited channels available in the BS in traditional SCNs.
- *Enlarge system coverage*: MSs that are located in dead-spot areas of the cellular networks can still establish call connections via multihopping [6,8,10,11,13,14,17]. Dead-spots may include the regions near the cell border, areas with deep fading (e.g. behind a building or in a tunnel), or areas where the high interference prevents a clear reception of cellular signals. Fig. 3 shows in more detail the enlargement of system coverage. MSs in dead spots, e.g. in the underground train system, can have their traffic relayed by other MSs over multiple hops before it is finally received by the BS.
- *Improve routing reliability*: In pure ad hoc networks, the routing path is often vulnerable to the node mobility and node failure [3]. In MCNs, routing decisions can be aided by intelligent BSs and the number of wireless hops in a routing path can be reduced through the use of the wired infrastructure [7,10,21–23], therefore improving the routing reliability.

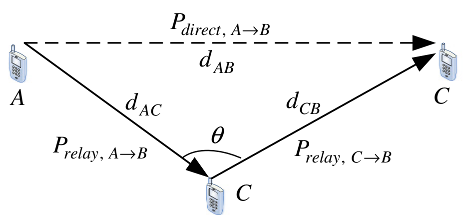

Fig. 2. Direct transmission vs. multihop transmission.

2.2. Drawbacks of MCNs

Besides the attractive advantages brought by MCNs, there are also some drawbacks that form the main resistance preventing the forthcoming implementation and commercialization for MCNs. The drawbacks of MCNs are listed as follows:

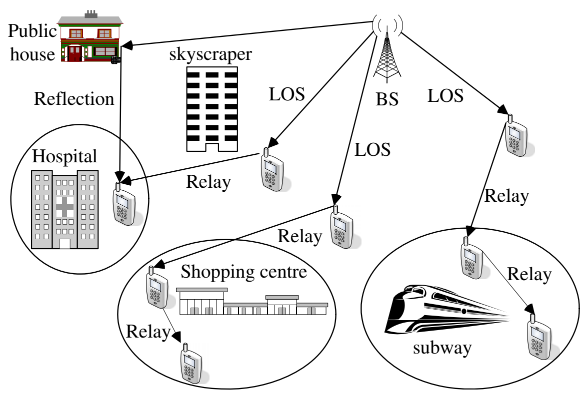

Fig. 3. Coverage extension to dead spots by relaying.

- *High system complexity*: MCNs are hybrid in nature and this causes increased system complexity, such as handover, routing and resource management for peer-to-peer communications, as compared to the SCNs or the MANETs. For example, the handover is not only executed for MSs to move from a cell to another, it is also involved during peer-to-peer communications. Besides, the BS may need to take care of the routing mechanism for a large number of MSs, much larger than normal MANETs. Thus, the BS requires a large database to store the MSs' information, such as the location information, and a much more powerful computational equipment to determine the routing decision for the MSs. There are many other factors to make MCNs more complex.
- *Potentially weak security*: MCNs allow for multihop transmission through fixed or mobile RSs and it may cause weakened security when the relay channels are in the free radio frequency bands, such as the industrial, scientific and medical (ISM) band. In addition, the peer-to-peer communications may be exposed to potential frauds, especially when monetary transactions are concerned. Fortunately, Danzeisen et al. [24] proposed a feasible method to secure heterogeneous communications in cellular systems. The method uses the cellular network to offer authentication and key exchange for the establishment of a secured data multihop connection in the Virtual Private Networks (VPNs). If the multihop participating device supports the cellular network, it is referred as a cellular node and it can communicate with the BS directly for authentication and key exchange; otherwise, it is referred as a non-cellular node and it needs the help of one of its trusted cellular nodes in order to communicate with the BS for authentication and key exchange. This approach is based on the subscriber's trust in the cellular operator. Specifically, by inserting only the cellular operator for the signaling part, the method leaves the data transaction as the same procedure as in wireless ad hoc networks. Therefore, it can be probably extended and applied in MCNs.
- *Challenging AAA procedure*: In MCNs, it becomes a challenging issue to perform the AAA procedure, especially for the accounting part. For example, a MS occupying the system bandwidth may not be transmitting data for itself, but relaying data for another MS; it is not an easy problem on how to charge this call over multiple hops through mobile relay stations. In particular, in case of the scenarios where the RSs are using the ISM band for data relay, not the cellular band, it becomes a controversial issue if we should charge them. In Section 5, we will look at this question using an economic perspective.
- *Delay*: Due to the use of multihop transmissions, packets may be buffered at the RSs. As a result, the end-to-end delay may be higher as compared to that of single-hop transmissions, especially when congestions occur due to high traffic loads.

3. Proposed MCN architectures

In the past few years, a number of MCN-type architectures have been studied. Some of these architectures proposed to deploy dedicated relaying entities for data forwarding. The relaying stations might be fixed network elements deployed by the service provider, which have lower cost and transmit power compared with the BSs. This type of relay stations is referred to as fixed relays. Fixed relays will be less expensive than the cellular BSs or the WLAN APs, as they do not require a wired backhaul connection. As a matter of fact, this absence of a wired backhaul connection is the distinguishing feature of a fixed relay. Alternatively, a MS in the system may play the role of data forwarding for other MSs. This type of relay stations may be referred to as mobile relays. Lastly, a combination of mobile relays and fixed relays is also feasible in MCNs, which is referred to as hybrid relays.

The proposed architectures can be classified based on the type of relay stations used, namely fixed relays, mobile relays and hybrid relays: (i) MCNs with fixed relays, (ii) MCNs with mobile relays and (iii) MCNs with hybrid relays.

3.1. MCNs with fixed relays

MCNs with fixed relays use dedicated and fixed devices as relaying entities to forward traffic from a MS to the BS/AP.

3.1.1. iCAR

The architecture proposed in [17], namely integrated cellular and ad hoc relaying (iCAR), features a typical example for MCNs with fixed relays, which makes use of the conventional cellular technology and ad hoc networking technology to realize the dynamic load balancing. The key idea of iCAR is to strategically locate a number of fixed relays, called ad hoc relay stations (ARSs), and use them to divert traffic from one possibly congested cell to other non-congested cells. Consequently, the congestion can be mitigated or even eliminated. Next, iCAR makes it possible to handle handover calls for MSs moving into a congested cell, or to accept new call requests originated from MSs in a congested cell. As shown in Fig. 4, if a MS *X* does not find a *cellular* frequency channel in cell *B* to set up a communication link with BS *B*, it will send the traffic to its nearest ARS, *ARS* 1, using frequency bands other than the cellular band, such as the ISM band. The *ARS* 1 will relay the traffic, using the ISM band again, to another ARS, *ARS*

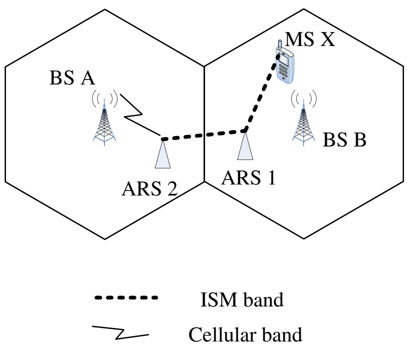

Fig. 4. The primary relaying strategy in iCAR.

2, in the neighboring cell, cell *A*. Finally, *ARS* 2 will forward the traffic to BS *A* using the cellular frequency channel. This provides a cost-effective way to overcome the congestion problem by dynamically balancing the traffic load among different cells. Besides the load balancing, iCAR is also able to extend the coverage of traditional SCNs. This is true because if a MS is out of the BSs' coverage, it can access the system by relaying its packets through ARSs.

The strategy on deploying ARSs is investigated in [25] which studied how to generate a scale-free topology for ARSs so that scalability can be achieved. Subsequently, by using the scale-free topology of ARSs, they proposed a load-balancing-based routing scheme for iCAR systems so that the system is more robust to BS failures and the available resource can be used efficiently. Furthermore, the performance analysis of iCAR is presented in [26]. The analysis is performed by a two-dimensional Markov chain model based on the finite number of orthogonal channels for cellular band and finite number of orthogonal channels for ISM band. In addition, the effect of the interference caused by other users using the same band on the number of relay channels in ISM band is also studied.

3.1.2. VCN

Kudoh and Adachi [27] proposed the concept of virtual cellular network (VCN). As shown in Fig. 5, each VCN consists of a central port (CP) and a lot of distributed wireless ports (WPs), which are equivalent to fixed relays. The CP functions as a gateway to the network, similar as the BS in a cellular system. A virtual cell is formed by grouping a number of distributed WPs and this grouping can be different for each user. In particular, the virtual cell size for the uplink may not be the same as for the downlink. However, how to group the WPs so as to form a virtual cell is not explicitly discussed in [27].

Furthermore, a MS is allowed to communicate with multiple WPs simultaneously to benefit from the site diversity. Multihop transmission is performed among WPs and each WP acts as a site diversity branch. Consequently, VCNs can significantly reduce the transmit power of a MS and the total transmit power of WPs.

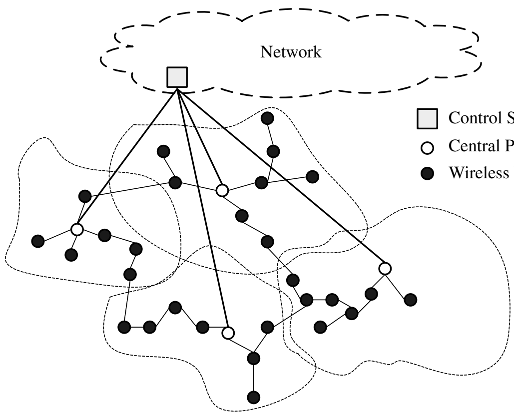

Fig. 5. Virtual cellular network.

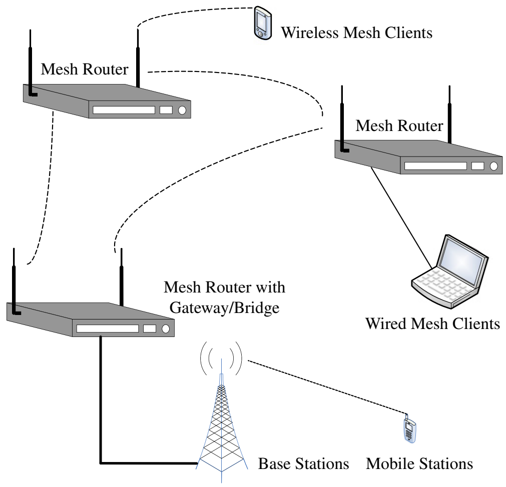

Fig. 6. Integrated wireless mesh networks with cellular networks.

3.1.3. Wireless mesh network

Wireless mesh networks (WMNs) have emerged as an important technology to provide high data rate services by means of multihop transmissions [28], which are undergoing rapid progress and inspiring numerous deployment. As shown in Fig. 6, WMNs usually consist of mesh routers and mesh clients. Mesh routers are normally stationary or with minimal mobility such that they form the backbone of WMNs and provide radio access for both mesh clients and conventional clients. The architectures of WMNs can be classified into three groups, namely infrastructure/backbone WMNs, client WMNs and Hybrid WMNs. For the infrastructure/backbone WMNs, some mesh routers are with gateway functionality and they enable integration of WMNs with traditional cellular networks, or external IP network for Internet connection. In particular, mesh clients may communicate with BSs with the aid of mesh routers, especially those with gateway/bridge to cellular networks. The mesh routers can be connected to BS through wireless or wired connections. Thus, we may treat mesh routers as fixed relay stations and WMN architecture as a special type of MCN architectures. In addition, WMNs can also be integrated with other wireless technologies, such as Wi–Fi, Worldwide Interoperability for Microwave Access (WiMAX) and wireless sensor networks. This feature of WMNs tallies with the ultimate goal of realized ubiquitous seamless wireless access in MCNs.

The main technical issues in mesh network development, which may include topology creation, routing, medium access control, security, quality of service and power efficiency, have been discussed in [29].

3.2. MCNs with mobile relays

MCNs with mobile relays propose to use MSs as relaying entities to forward traffic from a MS to a MS/BS. This approach avoids the installation of any additional network devices for the purpose of data forwarding.

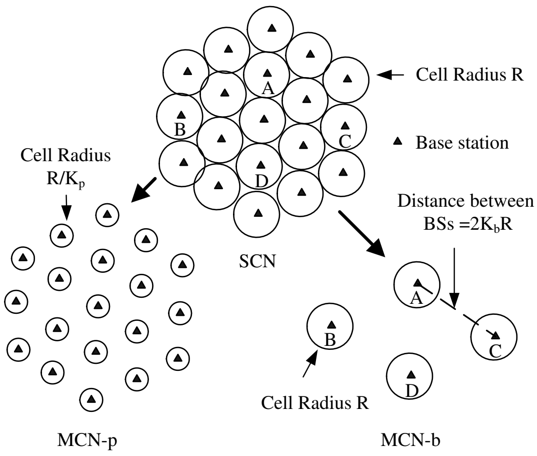

Fig. 7. Two ways of constructing MCNs.

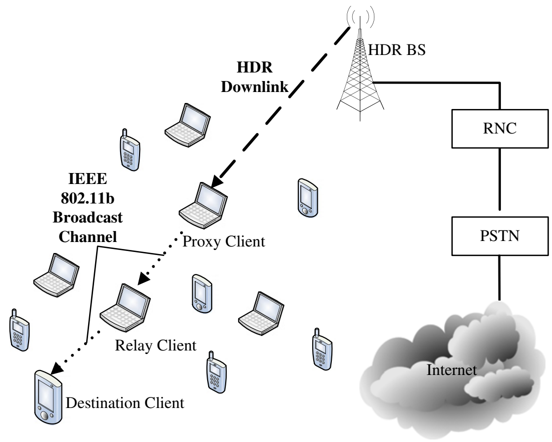

Fig. 8. Illustration of the UCAN architecture.

3.2.1. MCN [5]

Lin and Hsu proposed multihop cellular network [5] in the year 2000, which is considered as one of the few pioneer works reported in the literature using multihop transmissions in the cellular networks. They pointed out two ways to construct a MCN, which are shown in Fig. 7. One is referred to as *MCN-p*, which reduces the transmission range of a BS (or MS) and keeps the same number of BSs in the service area. The other one, *MCN-b*, on the contrary, reduces the number of BSs such that the distance between two neighbouring BSs becomes larger while keeping the transmission range of a BS or a MS. In both cases, the MS may not be able to reach the BS within one hop. Thus, multihop transmission through peer-to-peer communications among MSs, where some MSs act as mobile RSs, is necessary to communicate to the BSs. If a MS can not communicate to a BS due to out of the transmission range, it will reach the BS via a mobile RS. However, how to select a mobile RS is not explicitly mentioned in [5]. Consequently, the network operators could use MCNs for data services with high data rate requirements and continue with SCNs, such as GSM, for traditional voice calls. Hence, MCN does not have a problem to fit into the current state of technology.

In an effort to show the advantages of MCN, Lin and Hsu have considered only intra-cell network traffic. However, under inter-cell traffic conditions, the benefits of spatial reuse through peer-to-peer communications, if any, and the effectiveness of the MCN architecture might be poor.

3.2.2. UCAN

In the 3G wireless data networks, channel quality usually determines the QoS of the connection from a MS to its BS. When MSs are experiencing poor channel conditions, they can only have low data rate connections. This bottleneck actually limits the aggregate throughput of a cell. However, in order to maintain fairness, it is necessary to provide high data-rate services to any user in the cell. In [16], Luo et al. devised a new MCN-type architecture, namely unified cellular and ad hoc network (UCAN), by opportunistically using ad hoc network bandwidth, such as ISM band, for traffic relaying. As shown in Fig. 8, UCAN consists of a 3G cellular network, i.e. CDMA 2000 Evolution-Data Only ($1 \times$ EV-DO), also known as High Data Rate (HDR) [30], and Wi–Fi [31] to provide high data services for any user. If the HDR BS is not able to provide a high data rate to a specified MS, the HDR BS will forward the traffic to a proxy, a Wi–Fi terminal, which will relay the traffic to that MS.

For the proxy discovery, Luo et al. proposed two algorithms—*greedy* and *on-demand* proxy discovery algorithms. In general, the *greedy* proxy discovery protocol is proactive and the *on-demand* proxy discovery protocol is passive. The *greedy* proxy discovery requires a greedy path to reach a proxy client with high HDR downlink channel rate. A greedy path is constructed by a mobile client forwarding the route request message (RTREQ) to its neighbor client with the best HDR downlink channel rate for *each* hop. However, this greedy path may not always locate the proxy client with the best overall channel rate for the destination client. The *on-demand* proxy discovery always finds the proxy client with the best channel rate at the expense of RTREQ message flooding. The drawback encountered in UCAN is the potential stability issue related to the interference in the unlicensed ISM band.

Later, Feeney et al. [32] proposed a similar architecture that allows replacing a low data rate transmission with a two-hop sequence of shorter range, to provide higher data rate transmissions, using mobile relays. The difference from [16] is that a new relay proxy discovery protocol, opportunistic relay protocol (ORP), is proposed and studied in [32]. ORP allows MSs to increase their transmission data rate using a two-hop transmission with shorter transmission range in each hop, by using an intermediate MS as a relay, such that a higher data rate can be achieved with the shorter transmission range. Furthermore, ORP differs from the proxy discovery algorithms proposed in [16] in discovering proxy experimentally by opportunistically making frames available for relaying. MSs identify them as suitable relays by forwarding these frames. Lastly, A distinct feature of ORP is that it does not rely on observations of the received signal strength to infer the availability of proxy and transmit rates.

3.2.3. cMCN

Enlightened by the concepts of the microcellular/macrocellular hierarchically overlaid system [15] and the MANETs clustering [33], Li and Chong recently proposed clustered multihop cellular networks (cMCNs) and studied a fixed channel assignment (FCA) scheme in [7], and a dynamic channel assignment (DCA) scheme in [34] for cMCNs. The key idea behind cMCN is to apply the MANET clustering in SCNs so that we can achieve the characteristics of microcell/macrocell hierarchically overlaid structure. As shown in Fig. 9, the BSs in traditional SCNs will cover the whole macrocell with a radius of r_M. In the proposed cMCN architecture [7], the original macrocell area is divided into seven microcells (or clusters) with a radius of r_m; with one center microcell and six surrounding *virtual* microcells. The transmission range of the BS and MS is reduced from r_M to r_m in order to increase the spectral efficiency.

The proposed cMCN uses a DIP acting as a clusterhead in the center of each *virtual* microcell. The DIPs are installed to extend the coverage of the BS in terms of control information exchange and coordinate the peer-to-peer transmissions. For example, DIPs can help the BS to perform the AAA function; it also can help the BS to select and authorize a MS as a RS. The functions of the DIP are to allocate channels to the MSs within its cluster, select a MS as a RS, and determine the routing path. Different from the ARSs in iCAR [17], DIPs are not involved in data relaying and its complexity is much lower than a BS, so does the cost. The drawback of cMCN is that network operators need to deploy the DIPs, which will give rise to additional cost.

3.2.4. PARCelS

For iCAR [17], it can incur considerable cost to install a number of ARSs in cells. To solve this problem, Zhou and Yang proposed pervasive ad hoc relaying for cellular systems (PARCelS) in [18], which can be treated as an iCAR system with mobile relays. The word "pervasive" comes from the fact that PARCelS does not need the fixed relays as ARSs in iCAR. Furthermore, they proposed a load-balancing algorithm, which is actually a combination of proactive load-balancing and reactive load-balancing. Computer simulation results show that PARCelS is scalable and cost-effective. However, the mobility of mobile relays may have an adverse effect on the performance of PARCelS and hence coordination over the mobile relays is required.

3.2.5. CAMA

A cellular aided ad hoc network (CAMA) architecture was proposed in [21] and it is operated in places where a MANET overlaps a cellular network where the data is relayed through MSs. The servers that are in charge of operating CAMA are called CAMA agents. Each CAMA agent is connected to several BSs to manage the control information related to multihop transmissions. Through cellular radio channels with the help of BSs, MSs may contact CAMA agents to exchange the routing and security information. In addition, MSs can perform route discovery to identify the mobile RSs with the aid of CAMA agents or through beacon message exchange. Therefore, a CAMA agent functions as a position information server and consequently, CAMA is less vulnerable than *pure* ad hoc network.

3.3. MCNs with hybrid relays

MCNs with hybrid relays adopt both fixed relays and mobile relays.

3.3.1. HMCN

For MCNs with hybrid relays, Li et al. [6] proposed hierarchical multihop cellular network (HMCN). Additionally, a one-level version of HMCN was proposed in [22] and called cellular based multihop (CBM) system. As shown in Fig. 10, multihop cells are included as sub-cells in HMCN, where the multihop communication path is established through the multihop capable nodes (MHNs). Note that MHNs can be fixed relaying entities deployed by the network operator or mobile nodes (MNs) with multihop communication capability; fixed MHNs or mobile MHNs. For fixed MHNs, also called extension points (EPs), they are relaying devices deployed by the network operator at strategic locations. Fixed MHNs are comparable to the ARSs in iCAR [17], but their purpose is more related to enhance coverage of high data rate access. Mobile MHNs are actually MSs with

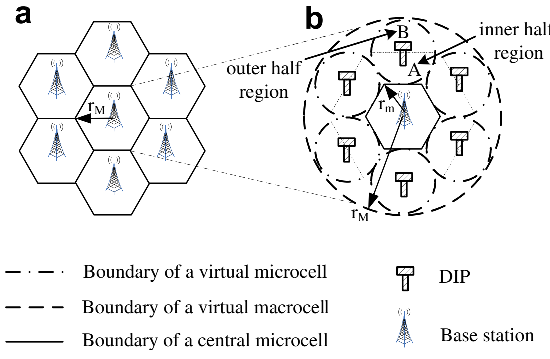

Fig. 9. Illustration of the cMCN architecture.

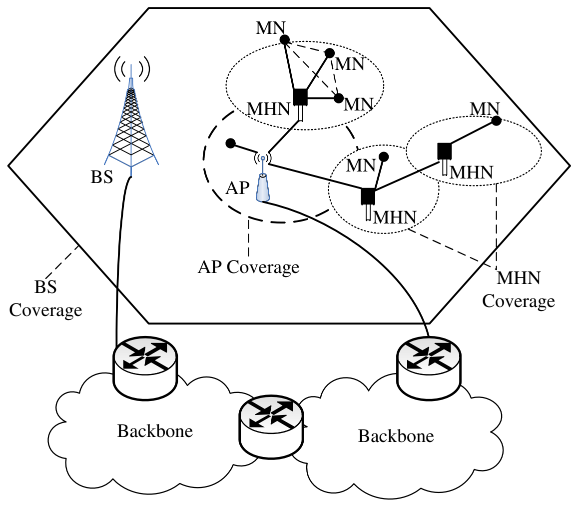

Fig. 10. Cell and multihop cell in HMCN.

multihop communication capability. With the aid of MHNs, multihop communication is realized in HMCN.

When fixed MHNs are used, the AP-MHN link should be known in order to optimize the overall performance of HMCN. In addition, a fixed MHN should have additional intelligence such as full scheduling capacity and processing the forwarding data in the baseband, instead of being a simple direct repeater. Next, the locations of fixed MHNs are pre-determined and help yield the highest benefit. Routing becomes simple if the AP knows where to find a suitable MHN. Furthermore, from the view of MSs, MHNs are equivalent to *simplified* APs. Finally, adaptive antennas can be equipped in fixed MHNs to further improve the data rate [8].

When mobile MHNs are used, a location controller is necessary to store the information of locality and neighborhood of each MS. Furthermore, each MS should be equipped with at least two sets of air interfaces, which operate in separate frequency bands. In this way, each MS can support multihop communication. The range of multihop cell is dynamically changing. Several routing schemes were compared in [6] and it was found that routing with information provided by the cellular infrastructure would consume the lowest overhead and exhibit excellent scalability.

To summarize, several benefits offered by HMCN [6] include coverage extension, transmit power reduction, capacity gain, low-cost deployment and optimized resource control. However, issues related to power control and resource management have not been investigated.

3.3.2. MADF

Wu et al. [19] proposed mobile-assisted data forwarding (MADF), which actually combines the characteristics of architectures proposed in iCAR [17] using fixed relays and PARCelS [18] using mobile relays. In MADF, a forwarding agent (equivalent to a relay) could be a repeater placed around the boundary of a cell or another MS. Under MADF, the cellular channels are divided into two groups—*fixed* channels and *forwarding* channels, where forwarding channels will be devoted to diverting traffic from a congested cell to a non-congested cell. In this way, the system performance can be greatly improved under some delay constraint. A similar concept is proposed by Yamao et al. [10], namely Multi-hop Radio Access Cellular (MRAC) scheme. For example, two types of hop stations (equivalent to relays) are assumed in MRAC—one is a dedicated repeater installed at a good propagation location and the other is simply a MS. However, the path diversity effect is purposely employed in MRAC, which is also studied in [23]. The path diversity is very helpful to solve problems such as AP failures, hand-off procedures and weak multihop connections.

3.4. Other MCN proposals

Although the three groups of MCN architectures cover most of the proposals, there are few that are not discussed above due to their special characteristics to include special techniques. Zadeh et al. [35] proposed the Self-Organizing Packet Radio Ad Hoc Network with Overlay (SOPRANO) and investigated several techniques, such as bandwidth allocation, access control and routing to increase the system capacity. Multi-user detection (MUD) was also adopted in SOPRANO to enhance the performance. Safwat proposed ad hoc-Cellular (A-Cell) relay [11], which adopts mobile BSs with directional antennas to reduce power consumptions and enhance the coverage and throughput. More interestingly, Barbarossa and Scutari proposed to take advantage of the virtual antenna array formed by the antennas of the cooperating MSs and transmit their data to the BS with much lower transmit power [9]. However, the cooperating MSs need to share their data first, which gives rise to considerable amount of security problems.

4. Comparisons and discussions among the proposed architectures

In order to compare the three groups of existing MCN architectures in terms of relay models, fixed and mobile, we have chosen the following criteria to compare the implementation issues of fixed relays and mobile relays in MCNs: cost (including device cost and deployment cost), power supply, network planning, routing protocol, security handling, adaptation to network growth and quality of service. The three types of MCN architectures can be compared below using the selected criteria:

- *Cost*: Using fixed relays will increase the deployment cost of putting fixed relays although a fixed relay is much cheaper than a BS/AP. On the contrary, using mobile relays will not give rise any deployment cost. However, for both types of relays, intelligent network protocols, such as routing, handover, and radio resource management, should be employed and this leads to additional cost in purchasing the related software. About the device cost, mobile relays need higher device cost because the MSs will act as a relay to receive data from one MS and forward the same data to other MS. Therefore, the mobile device may need two antennas to avoid the self-interference. Also, the MSs need a powerful computational unit to handle the complex routing algorithm.
- *Power supply*: There is no power consumption issue for fixed relays. However, the power consumption of the RSs becomes a critical issue in MCNs with mobile relays. If a MS is frequently selected as a mobile relay, its power may be drained very fast. Thus, some incentive schemes [36] should be incorporated to encourage more MSs to participate in the role of RSs and optimize the route discovery and maintenance in order to save the mobile RSs' power.
- *Network planning*: When fixed relays are adopted, their locations should be determined strategically in the network by considering the tradeoff between the optimal network performance and the number of fixed relays [25]. However, when mobile relays are adopted, there is no such trouble.
- *Routing protocol*: It will ease the design of routing protocol by using fixed relays rather than mobile relays because the MSs will know the locations of the fixed

relays to help make the routing decision. Besides, using fixed relays the network operator has less difficulty in handling the mobility of MSs. However, if mobile relays are used, the routing issue becomes complicated and location information of mobile relays should be stored and updated periodically. Also, the routing paths will be changed often due to the mobility of the mobile relays. It may increase the system complexity.

- *Security handling*: It is easier to handle the security issue in a MCN-type system using fixed relays than that in a MCN-type system using mobile relays. This is because fixed relays are deployed by network operators and MSs can trust them without bothering the security key exchange. However, for mobile relays, how to authenticate a secured RS becomes difficult and a possible solution with the aid of the cellular infrastructure is discussed in [24].
- *Adaptation to network growth*: When fixed relays are used, the network operator needs to re-plan and redeploy them by considering the new traffic characteristics and other related issues. On the contrary, when mobile relays are used, the MCN system can adapt the network growth without difficulty.
- *Quality of service*: MCNs with fixed relays will give rise to more stable routing and less end-to-end transmission delay of packets. Hence, delay-sensitive services can be accommodated. On the contrary, MCNs with mobile relays may experience the problems with vulnerable relay paths due to the mobility of RSs. Although this difficulty can be alleviated by employing intelligent route discovery and maintenance algorithms, MCNs with mobile relays will result in longer end-to-end transmission delay due to longer time to select a routing path as compared to MCNs with fixed relays.

The characteristics of MCNs with hybrid relays can be inferred from those of MCNs with fixed relays and MCNs with mobile relays. However, the MCN with hybrid relays must be designed carefully so that it can optimize the performance and minimize the drawbacks from both relays—fixed and mobile. Otherwise, it may adversely affect the outcome. The above comparison criteria enable a network operator to gain insights into the different aspects of implementation for different relaying models.

In addition, we provide a comparison of some typical MCN architectures discussed in Section 3 and Table 1. For

Table 1
Comparison of selected MCN architectures

Architecture	Description	
iCAR	Wireless technology	Cellular system, WLAN
	Relaying entity	Fixed relaying devices called ad hoc relay station (ARS)
	Interface	Dual interfaces
	Objectives	Solving the congestion problem by diverting traffic load from congested cell to neighboring non-congested cells
	Implementation	Using fixed relaying devices, i.e., ARS, which are placed strategically in the network for traffic relaying
MCN	Wireless technology	Cellular system, WLAN
	Relaying entity	Mobile stations
	Interface	Dual interfaces
	Objectives	Solving the capacity enhancement problem by reducing the number of BSs for upgrading
	Implementation	Reducing the transmission power of the BS and MS, thus increasing the spatial reuse of limited bandwidth
UCAN	Wireless technology	3G Cellular system, WLAN
	Relaying entity	Mobile client
	Interface	Dual interfaces
	Objectives	Increases the downlink throughput of cellular system by opportunistic use of IEEE 802.11 based ad hoc networks. It also maintains throughput gain fairness by refining 3G BS scheduling algorithm
	Implementation	Relaying traffic in HDR downlink to the proxy client, then forwarding it through several intermediate clients before finally the traffic arriving at the destination client. The route request message is initiated by the destination client and it also acts as a route establishment. There are two proxy discovery protocols proposed in UCAN—*greedy* and *on-demand* proxy discovery
cMCN	Wireless technology	Cellular system
	Relaying entity	Mobile station
	Interface	Single interface
	Objectives	Providing high system capacity, facilitating the implementation of channel assignment schemes and relaying is implemented using cellular frequency band
	Implementation	Microcell/macrocell hierarchical overlaid structure is formed by applying MANETs clustering in traditional cellular networks
HMCN	Wireless technology	GSM, UMTS, WLAN
	Relaying entity	Multihop capable node (MHN). It can be fixed relaying devices (extension points) or mobile stations
	Interface	Dual interfaces
	Objectives	Providing high data rate services for cellular system user through the possible use of WLAN access and high mobility Internet access for WLAN user by allowing vertical handover to cellular system
	Implementation	Introducing a layered architecture of several wireless systems with overlapped coverage. Multihop communication is mostly performed in the WLAN layer

MCNs with mobile relays, we have chosen MCN, UCAN and cMCN as typical architectures because they represent different typical ways of using mobile relays: (i) MCN randomly selects an idle MS as a RS; (ii) UCAN selects a MS with a better channel condition and a higher data rate as a RS; (iii) while cMCN selects a MS as a RS with the coordination of a DIP in each *virtual* cluster (microcell). The comparison of other architectures can be deduced using the same methodology.

It could be seen from Table 1 that different existing MCN architectures had been proposed for different objectives. Therefore, it is not an easy task to achieve a unified MCN architecture with ubiquitous seamless access for 4G mobile networks. With the recent standardization of WiMAX (IEEE 802.16) as a new technology for broadband wireless access, which could operate either like a single-hop cellular system in PMP (Point-to-Multipoint) mode or like a multihop relay system in MESH mode [37], it is interesting to watch and it remains to be seen how WiMAX may impact the design of MCNs.

5. Economics for MCNs

In this section, we take an economic perspective on the deployment of MCNs. In particular, we focus on the economic considerations for deploying relay stations in MCNs. Similarly, two types of relay stations can be considered: fixed and mobile relay. For simplicity's sake, MCNs with fixed relays are referred as fixed-relay MCNs and MCNs with mobile relays are referred to as mobile-relay MCNs.

5.1. Implementation using fixed relays

The cost of deploying a fixed relay is generally expected to be lower than that for a BS for several reasons [12]. First, with a smaller coverage area, the transmit power requirement for a relay would also be lower than that for a BS, which in turn permits a more economical design of the amplifier used in the relay. Secondly, for the same reason, a relay typically does not need to be mounted as high up as a BS, hence reducing operating expenses such as tower leasing and maintenance costs for the MCN operator. Furthermore, unlike a BS, a relay does not need to be wired to a backhaul, but only relays traffic between the BS and end terminals wirelessly. Thus, the cost of a wired backhaul connection can be eliminated.

The use of such low-cost relays allows the fixed-relay MCNs to require fewer expensive BSs to cover the same area as traditional SCNs. This leads to a common claim that a fixed-relay MCN will be more cost-efficient to deploy than a traditional SCN, which however may not be always true. It is true provided that the cost savings from the number of saved BSs are more than the cost of deploying the required number of relays, which in turn depends on the relaying techniques used and the service level to be provided. In [38], Timus evaluated the particular case of a greenfield-operator scenario and by the use of a modified "Nearest relay with Forward Progress" (NFP) routing and space–time division multiple access (STDMA) scheduling scheme. In addition, Timus found that fixed-relay MCN (known as hybrid system in the paper) is economically feasible if the cost of a relay is 3–9% of the cost a BS, depending on the desired service level.

5.2. Implementation using mobile relays

In contrast, the deployment of a mobile-relay MCN does not depend on the cost of a relay, but on the willingness of mobile users in the network to act as relays. From the operator's point of view, this is a major challenge because there is little benefit to a user to willingly participate in forwarding another user's traffic as doing so will sacrifice its own energy and bandwidth resources. Thus, incentives must be provided to compensate each user for its resources expended in relaying for the benefit of other users.

In the sequel, we elaborate on the following considerations: (i) forms of incentives to stimulate forwarding; (ii) methods of charging for usage of relaying service; (iii) methods of remunerating for provision of relaying service; (iv) security against fraud and attacks.

5.2.1. Forms of incentives to stimulate forwarding

Monetary incentives are the most common form of incentives used by network operators to reward users who have participated in forwarding traffic for other users. The monetary reward may come in different forms: as an amount credited to the billing accounts which users maintained with the operator [36]; as electronic tokens which users could redeem for monetary payments [39]; as a 'top-up' of the credit value of a smart card which users use to pay for transmitting their own packets [40]; or as a discount in the user subscription price for accessing the network [41]. In addition to monetary rewards, another form of incentive could be in terms of improved service levels, such as better performance and access to the network resources for cooperating users.

In [42], the authors further proposed to stimulate forwarding by allowing an originating source to delegate part of its bandwidth to a relay for forwarding its traffic. This is to avoid depriving the relay from transmitting its own traffic when it uses its bandwidth to forward the traffic of others. In TDMA systems, such resource delegation could be accomplished by means of subslotting, i.e. dividing the time-slot of a source into source and relay subslots, and delegating the relay subslot to the relay for forwarding the source's traffic. For systems based on CDMA, resource delegation may also be carried out by means of subcoding or multicode transmissions.

5.2.2. Methods of charging for usage of relaying service

There are different schemes of charging users for packets sent over multiple hops. In [36], the source of a packet is charged an amount that is proportional to the packet size, and the relay nodes involved in forwarding the packet to the destination are paid an amount that is similarly in proportion to the packet size. The destination is also initially charged a small amount and refunded only if it sends an acknowledgement for the packet it receives, which is necessary for the operator to know that the packet has been delivered. As such a charging scheme depends only on the packet size and not the number of relays on the packet's path, the operator may incur a loss when the route is long, but profit when the route is short.

A more flexible form of charging involves allowing the source node to specify the cost it is willing to pay for its packets according to the importance of having them delivered, and each relay node to indicate the price it is willing to accept to forward packets based on its remaining energy [39]. A shortest-hop path consisting of relay nodes that accept the price of the source is then setup for forwarding. Alternatively, the cost of a relay may be assigned by the BS based on its importance in the routing topology, i.e. the more critical is the node in contributing to successful relaying of the packets from the source, determined by means of its node degree, the more costly it would be [43].

The additional cost of retransmissions by relay nodes during forwarding is considered in [44]. To be compensated for expending extra power to forward data for other nodes, each relay node may inform BS of its number of retransmit attempts by including this information into the source route field of the IP header.

5.2.3. Methods of remunerating for provision of relaying service

The relay nodes that participated in forwarding traffic of other nodes could be remunerated by the network operator in a number of ways. By remunerating, a suitable equivalent will pay to the relay nodes in return for the forwarding service that they have rendered. In [44], the authors proposed to reimburse the relay nodes either on an end-to-end or hop-by-hop basis. In the end-to-end scheme of reimbursement, the relay nodes are reimbursed only when the packets they forwarded are received successfully by the destination. The destination in turn would transfer the pricing information for reimbursing the relay nodes through its periodic neighbor updates to the BS. On contrary, a hop-by-hop scheme of reimbursement requires each relay node to maintain information such as the amount of traffic it has forwarded and their sources and sends this information along with its neighbor updates to the BS.

In [36], an end-to-end scheme is similarly proposed, but considers remunerating upstream (source → BS) and downstream (BS → destination) nodes separately, i.e. upstream nodes are remunerated when packets they forwarded arrived at the BS and downstream nodes are remunerated when packets are delivered and acknowledged by the destination. A similar hop-by-hop scheme but uses probabilistic payment is proposed in [39]. Under this scheme, a source attaches a token to each of its packet, and all relay nodes verify whether the token is a 'winning ticket' for them to make a reward claim by applying the token and their secret key to a probabilistic function. If the result is positive, the relay node sends a reward claim using a direct uplink to the BS.

5.2.4. Security against fraud and attacks

The hop-by-hop scheme is comparatively more prone to fraud as unlike in the end-to-end scheme where the information for reimbursing relay nodes is provided only by the packet's destination, herein the information is provided by each relay node to the BS to claim for its own rewards. Thus, there is an issue of trust here, and to prevent nodes from providing false information, either a tamper-proof pricing and security module could be used at the mobile nodes, or the source may also furnish the BS with information regarding the traffic it generates [44]. In addition, the BS could further verify the reward claim of a relay node with its two neighboring nodes (successor and predecessor) on the packet's path, so that any reward claim for packets which the source generated but were not received by the relay node for some reason (via its predecessor), or the packets were received by the relay node but it did not forward them (via its successor) to the destination, could be detected [39].

Besides fraud, attacks may be launched by malicious nodes to deny others from receiving forwarding service by repeatedly setting up forwarding paths without intending to use them, or to drain the battery of relay nodes by generating requests for large amounts of data that they do not intend to use. As a counter measure, it is proposed in [45] that attackers should be made to pay for their attacks by charging them a fee whenever they initiate the protocol to setup a session. In [40], the authors further considered charging nodes when they received packets that are meant to be forwarded, with the charge being a fraction of the reward they would obtain for forwarding the packets to their destination. Thus, a node is enticed to forward the packets rather than dropping them, in order to recover the costs of its reception.

6. Conclusions

MCN is an architecture that promises to harness the benefits of traditional cellular and emerging ad hoc relay systems, while mitigating the shortcomings of both. MCN enhances current SCNs through increasing their system capacity, allowing higher data rate services, balancing traffic load, alleviating capacity bottlenecks and enlarging system coverage. MCN also enhances current multihop ad hoc networks through improving their routing reliability. MCN is hence considered a promising 4G network candidate for future mobile communications.

In this paper, we revisited the concept of MCN and discussed the benefits that it could deliver. We then classified the proposed MCN-type architectures based on the relay stations used for multihop transmission. Next, we compared and discussed their respective technical strengths and weaknesses. Finally, we also discussed the economics on the deployment of MCNs. In particular, we focus on the economic considerations for deploying fixed and mobile relays.

Noteworthily, network operators should consider a tradeoff between the implementation complexity and the system performance of MCNs. Mobile relay system seems to be more economically feasible over the long term since they could adapt dynamically to network growth, although it would increase the complexity of MS design and routing protocol. The advances in IC design and microprocessor technologies would hopefully solve the problems in hardware design, whereas network researchers continue to research on the best performing MAC and routing protocol for the dynamic mobile relaying model. All these efforts shall bring MCNs into real implementation in the near future for 4G wireless communication systems.

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