Hybrid Wireless Networks: Applications, Architectures and New Perspectives

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Abstract: With the advent and ubiquitous of wireless technology, a wide range of advanced services are expected to be supported including appealing services that currently exist in wired systems. Nevertheless, the resource constraints in wireless environment may render difficulty to realizing all the desirable services. Consequently, an infrastructure with high data rate is necessary to complement the resource constraints and to act as anchor points linking mobile nodes to other fixed networks as the Internet. Hybrid wireless networks have emerged as a promising solution, allowing mobile clients to achieve service access in a seamless manner independent of their existence in Wireless LAN (WLAN) communication range. In this paper we address the benefits of hybrid wireless networks, showing their possible applications and presenting a classification for their emerging architectures. Also, we identify the research challenge arising from the problem of applying the grid computing concept in such hybrid wireless environment, showing the expected benefits from the aggregated fixed-mobile capacity. Finally, we propose our vision for a potential architectural model, which is expected to provide useful services by the network operator or the service provider in such a hybrid environment.

Keywords: *Hybrid wireless networks, WLAN, ad hoc network, grid computing, wireless grid*.

1. Introduction

Hybrid wireless networks are networks in which any mobile node in a wireless network may have connectivity, either directly or via a gateway node, to an infrastructure network. This latter network may be an IP network as the Internet, a 3G wide area wireless network, or an 802.11 local area wireless network. Actually, any other network technology may be considered. In this context, the notion of Intra technology and Inter technology appears. If a mobile node communicates with another network of similar technology, this can be seen as Intra technology hybrid wireless network. As for example, the case of a mobile node in an ad hoc 802.11 network communicating with an 802.11 Access Point (AP) in an infrastructure network. On the other hand, if a mobile node communicates with another network of different technology, this can be seen as Inter technology hybrid wireless network. As for example, the case of a mobile node in an 802.11 network communicating with a 3G network. Moreover, hybrid wireless networks may integrate both Intra and Inter technology cases and the mobile node itself may support heterogeneous technologies switching between them in an on-demand fashion.

There are several motivations for considering such hybrid networks design. Firstly, the required hardware already exists, where wireless access points are becoming ubiquitous and all laptops and many PDAs sold today are pre-installed with Wi-Fi. Also, some cell-phone manufacturers started offering smart phones that integrate Inter wireless technologies, with a focus on GSM and Wi-Fi. These smart phones can be used both to offer high bandwidth Internet access when an access point is available, as well as to carry voice conversations over organizations internal network or even home networks using VoIP techniques, thereby reducing operating costs. Secondly, orchestrating this available hardware to work as a hybrid wireless network can provide architectures deployments that allow users to achieve higher throughput and switch between different types of networks, having seamless access to integrated or distributed services. Consequently, several advantages to both users and service providers/network operators are expected. For example, through offering integrated services between a 3G network and an 802.11 network, 3G operators and Wireless Internet Service Providers (WISP) could attract a wider user base and ultimately facilitates the ubiquitous introduction of high speed wireless data. Such a combined service allows enhanced performance and low overall cost. In addition, through exploiting the ad hoc network potential, to extend the coverage zone of an infrastructure network, mobile users in a Wi-Fi hotspot region can achieve service access in a seamless manner independent of their existence in a WLAN communication range, allowing new business opportunities.

In fact, there is an increasing attention from the industry and the research community on such issue. As a result, some hybrid wireless network architectures have emerged combining multi-hop radio relaying and infrastructure support, aiming to provide high capacity wireless networks. Also, an emerging challenge, in this context, lies in introducing the computation grid concept in such hybrid wireless networks environment. One promising trend is to harvest the widespread resources of wireless mobile devices, such as PDAs and laptops, to be beneficially useful within one or more mobile grid clusters. On the other hand, mobile nodes could benefit from the large resources in the fixed grid clusters.

Furthermore, some standardization efforts are paying attention to hybrid wireless networks technology. The IEEE 802.11s (*targeted for June 2008*) is concerned with WLAN MESH networking, while the IEEE 802.11u (*targeted for December 2007*) considers the Interworking with external networks.
In this paper we review some proposed hybrid wireless networks solutions, presenting a classification for the emerging architectures in this context. We also identify some arising research challenges in this type of networks, stating the related existing solutions. Finally, we propose our vision in this problem giving some key issues in a potential architectural model for hybrid wireless networks. The rest of this paper is organized as follows; Section 2 presents a literature review. In Section 3, we derive a general classification for the existing types of hybrid wireless networks. Section 4 presents some important research challenges. In Section 5, we present some essential basics for an architectural hybrid wireless networks model. Finally, we conclude the paper in Section 6.

2. Hybrid wireless networks: Literature review

Although hybrid wireless networks are a promising domain, research on this area is still not intensively explored. In this section, we present the major research trends in this domain. The main treated aspects concern architectures, radio resources management, routing and security. In Section 3, we develop a classification for the existing types of hybrid wireless networks.

2.1 Architecture, resources management and routing issues

Ananthapadmanabha et al. propose a Multi-hop Cellular Network (MCN) as a novel cellular architecture in which a connection between a source and a destination located in the same cell is established over a multi-hop path [1]. The architecture considers two types of channels: a) data channel with transmission range equal to half the cell radius, and b) control channel with transmission range equal to the cell radius. The transmission power over the data channel is reduced to a fraction of the cell radius, increasing the spatial reuse. Consequently, higher throughput is achieved. In addition, a routing protocol is proposed with a route discovery phase and a maintenance phase, in which the base station (BS) is responsible for route calculation. This allow the battery conservation of mobile nodes (MNs). Although this work enhances throughput and battery lifetime, there is a risk of connexion dropping resulting from shared control channel saturation. Also, this architecture doesn't leverage the potential of ad hoc networks in extending the BS coverage area. A quite similar architecture named UCAN (Unified Cellular and AdHoc Network Architecture) is proposed by Luo et al. [14]. The difference with the previous approach is that in UCAN, the 3G BS forwards packets in a hybrid manner only for destination clients with poor channel quality. Those packets are proxied by some other clients with better channel quality. The proxy clients then use an ad-hoc network composed of other MNs and IEEE 802.11 wireless links to forward the packets to the appropriate destinations, thereby improving cell throughput. However this architecture doesn't extend the BS coverage area. Besides, hardware complexity (multiple air interfaces per MN) may cause MNs to quickly run out of battery.
Wu et al. propose an integrated cellular and ad hoc relaying (iCAR) system that enables a cellular network to achieve a throughput closer to its theoretical capacity [2]. This approach is based on dynamically balancing the load among different cells. As illustrated in Figure 1, a number of Ad hoc Relaying Stations (ARS) are deployed at appropriate locations. The ARSs serve to relay excess traffic from a heavily loaded cell to a lightly loaded cell in the same vicinity. ARSs communicate with BS in infrastructure mode, while they communicate with MNs and other ARSs in ad hoc mode. The coordination between BSs, ARSs and MNs is handled by a control protocol. This work leverages the potential of ad hoc networks achieving a throughput closer to cells theoretical capacity. However, some limitations are noticed as signalling overhead, non optimal routes and hardware complexity due to the number of radio interfaces that must be supported by the MNs. A similar approach, relaying excess traffic, is shown in MADF (Mobile Assisted Data Forwarding) architecture [3]. A main difference is that MADF doesn't use dedicated nodes to relay excess traffic as iCAR does, but rather MADF uses MNs.

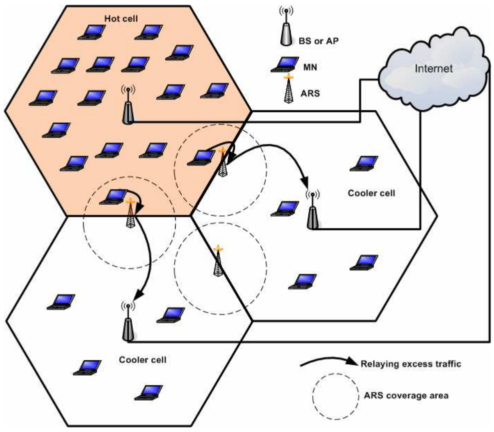

Figure1: iCAR architecture

Following the above trend, a more general architecture named SOPRANO (Self-Organizing Packet Radio Ad hoc with Overlay) is introduced in [4]. As shown in Figure 2, SOPRANO is a wireless multi-hop network overlaid on a cellular structure. The goal is to provide high data rate Internet access by using inexpensive dedicated relay stations. More channels are available in the network and path losses are reduced, thanks to cell splitting. Hence the network capacity can be maximized by choosing a suitable routing strategy which is a function of the techniques used in the physical layer. This approach can assure load balancing and potential throughput enhancement. Also, it succeeds in extending the BS zone without requiring multiple radio interfaces to be supported by MNs.

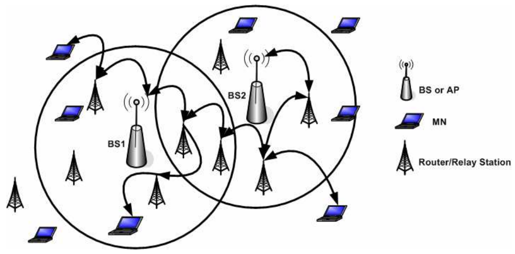

Figure 2: Load balancing through BS1 when BS2 is heavily loaded and reciprocally

Karrer et al. define a new architecture based on directional and omni-directional antennas deployed on fixed Transit Access Points (TAPs) forming a multi-hop wireless backbone with a limited number of wired ingress/egress points [5]. As shown in Figure 3, a multi-hop backbone mesh interconnects TAPs to mobile nodes and the wired Internet. The main limitation of this architecture is allowing only multi-hop connection to the TAPs from outside their coverage areas and not from inside those areas as well, which minimizes the performance.

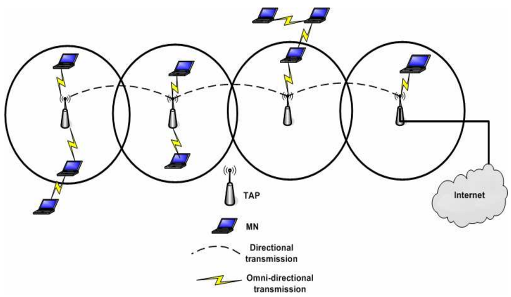

Figure 3: TAPs architecture

BAS (Business As uSual) project [6] plans to use a network of public buses to provide a wide range of services. An architecture is developed comprising ad hoc networks in term of wireless buses, and Access Routers (ARs) along the roadside serving as gateways to provide Internet access. A geographic forwarding protocol is developed making use of digital road maps to predict and avoid forwarding failure due ad hoc network partitions. Also, this approach employs a hybrid adaptive gateway discovery protocol to enable buses to access the Internet.

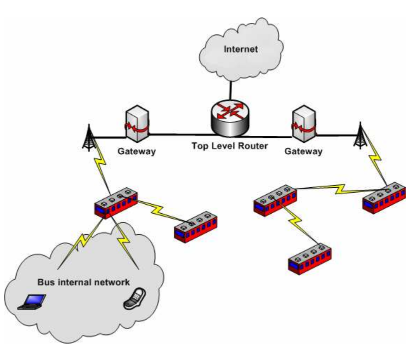

Figure 4: BAS system architecture

Zoican and Galatchi introduce a routing solution for ubiquitous mobile access to the Internet in a Hybrid Network Architecture (HNA) [7]. As shown in Figure 5, HNA consists of an ad hoc multi-hop wireless topology and a hierarchical infrastructure deploying multiple APs and a common gateway. A proactive routing solution (FMARP: Flexible Mobile Access Routing Protocol) is proposed. FMARP is a hierarchical protocol based on the construction of a load adaptive tree topology rooted at the gateway. Although FMARP tries to optimize the performance, HNA has two main drawbacks which are the bottleneck risk at the gateway and the signalling overhead.

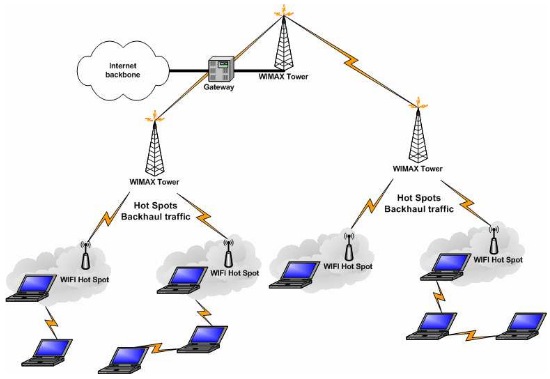

Figure 5: HNA system

A Roofnet 802.11 architecture consisting of unplanned node placement, omni-directional antennas and multi-hop routing is proposed by Bicket et al. [8]. Figure 6 illustrates this architecture. The goal is to evaluate the performance of a wireless mesh architecture providing Internet access with little deployment planning and little operational management. A performance evaluation shows that Roofnet's multi-hop mesh increases both connectivity and throughput compared to a hypothetical single hop network. Since this architecture is quite static, it cannot be considered as a reference model in a real dynamic and ubiquitous environment.

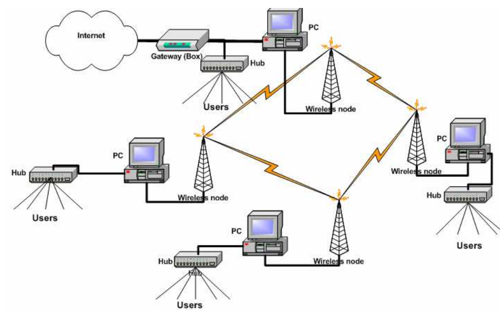

Figure 6: Roofnet architecture

Generally, we notice three trends for routing approaches in hybrid wireless networks architecture. One approach is to extend or adapt current ad hoc routing protocol like DSR or OLSR [9], a second approach combines MIP (Mobile IP) with some ad hoc routing protocols [10, 11] and a third approach maintains a connectivity tree or an almost optimal spanning tree rooted at the AP/BS or the gateway [7, 12, 13].

2.2. Security issues

Actually there are few contributions related to security. The work done in UCAN (Unified Cellular and Ad-hoc

Network architecture) [14] provides protection against selfish nodes attack. Individual hosts are prevented from deleting legitimate hosts or adding non-authorized hosts to the set of relaying nodes. However, this protection is limited to the case of non colluding nodes. In [15] Capkun et al. allow the anonymity and privacy of mobile hosts in a hybrid wireless network covered by several access points.

Solutions for security threats (impersonation, rate inflation, tunnelling / worm hole, DoS, path scrambling, black hole attacks) in hybrid wireless networks are investigated by Carbunar et al. [16]. A secure tree-based routing protocol is also introduced, establishing secure routes between the BS and MNs.

An authentication, authorization and accounting (AAA) scheme is proposed by Zhang et al., based on public key cryptography [17]. The notion of virtual operator is used. This approach converges both the AAA process and data transmission at the IP layer, and allows intermediate mobile ad hoc terminals to extend the APs service coverage. This work mitigates selfish nodes attack; however it does not integrate layer 2 security mechanisms causing it to be vulnerable to a wide range of layer 2 and DHCP attacks.

Finally, some work adapted 802.11i to the hybrid ad hoc network environment. Shaer et al. propose a secure handoff scheme [18] integrating the infrastructure mode and ad hoc mode of wireless networks. An extended 802.11i framework is implemented extending the APs operational range and taking advantages of 802.11i security. However, this approach is not adapted to the context of a general hybrid network as it does not support more than two hops between any mobile node and the AP. In [23, 24], 802.11i is adapted in vehicular communications on highways. A new architecture is proposed offering communication between vehicles as well as vehicular connection to the Internet. Ad hoc networking is used to extend the 802.11 APs zones, including intermediate nodes. However this approach does not offer a mobility management solution.

3. A developed classification for existing hybrid wireless networks

In this section, we develop a classification for the existing hybrid wireless networks. We define three main classifications for the existing architectures: Intra-cellular, Inter-cellular and Extra-cellular. In Intra-cellular architectures, each AP/BS communicates with any MN in its coverage area in a multi-hop fashion. On the other hand, in Inter-cellular architectures, each AP/BS communicates with any MN in the coverage area of other APs/BSs in a multi-hop fashion. Finally, Extra-cellular architectures enable an AP/BS to communicate with MNs that are not in the coverage area of any AP/BS. In this latter case, ad hoc networking is used to extend the coverage area of the AP/BS. Any of these classifications may employ dedicated relay stations (routers) or rather host-cum-relay stations. Further more, Intra/Inter cellular ad hoc mode architectures can be classified as multi-mode systems in which MNs act either in single-hop mode or multi-hop mode, or single-mode systems in which MNs act exclusively in multi-hop mode. Figure 8 illustrates this classification.

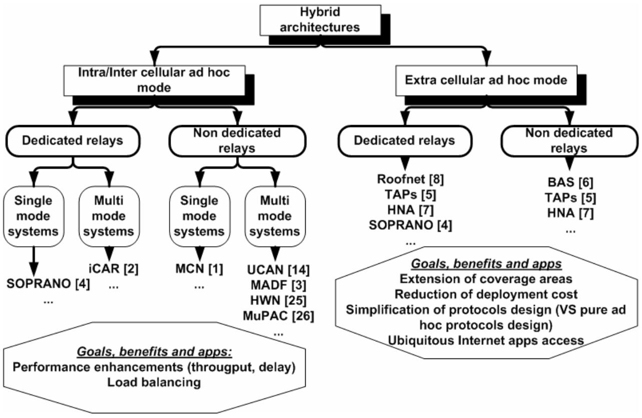

Figure 7: Hybrid wireless networks classification

4. Research challenges for hybrid wireless networks

Recent research efforts in hybrid wireless networks have come up with some protocols, models and applications aiming to provide a reference architecture for the future networks generations. Actually, numerous challenges still need a particular attention to support hybrid wireless architectures generalisation and putting to reality. These challenges are mainly related (but not limited) to signalling, routing, radio resources allocation, mobility management, security, incentives models and services discovery. It is essential to consider an integrated approach against these challenges avoiding independent solutions for challenges. In this section, we discuss some emerging research challenges in such type of networks, highlighting some interesting research directions in this area.

4.1 The concept of grid computing

Employing the grid computing concept in hybrid wireless networks can enhance signalling, radio resources allocation as well as service discovery. Grid computing enables distributed computing and resources virtualization such as processing, network bandwidth and storage capacity, creating a single virtual system. This can grant users seamless access to vast applications and IT capabilities. At a first glance, it seems that marrying mobile wireless consumer devices and high-performance grid computing would be an unlikely match. In fact, these individual computing devices may be resource-limited in isolation, while as an aggregated sum, they have the potential to play a vital role within grid computing. Actually four approaches have emerged considering wireless networks and grid computing: a) the wireless network, client of the grids in which wireless nodes use resources of the wired grids [19], b) the wireless network, server of the grids in which wireless nodes share their resources with the wired grids [20], c) the grids in the wireless network in which the grids are formed by wireless nodes [21] and d) the wireless network client and server of the grids in which wireless nodes use resources of the wired grids and at the same time share their own resource with them [22]. In hybrid wireless networks approaches (a) and (c) can be leveraged to alleviate/compensate the load on non dedicated relay stations. Firstly an infrastructure grid can be employed granting processing or storage services. Secondly, non relay nodes can grant the same services to balance the loads in the network. Generally, MNs can take advantages of an infrastructure grid to support the networks operations, thus reinforcing the stability and viability of hybrid wireless architectures. Finally, as introduced in approach (b), infrastructure grid can leverage hybrid wireless architectures capabilities in connecting a larger number of MNs, to aggregate MNs resources and use/trade them as an utility resource. This approach can allow new business models for operators or services providers.

4.2 Security

Security is a core challenge in the emerging hybrid wireless architectures. Many advances have already been done in the context of pure ad hoc networks such as those concerning key management, link layer security, secure routing and forwarding, secure end to end communications and application layer security. In the context of pure infrastructure networks, security solutions exist and are quite satisfying (802.11i, GSM, GPRS, UMTS, etc.). The main challenge for hybrid wireless networks is to leverage the infrastructure part of the network and adapt some approaches developed for pure ad hoc networks. The major trend when APs/BSs are not able to directly enforce security in the whole network, is to distribute some of their security privileges to authenticated relay stations which in turn are responsible of enforcing security policies locally. This trend can be seen as a security grid between all the security enforcing entities.

4.3 Routing

Compared to pure ad hoc routing protocols, routing in hybrid wireless networks is dramatically simplified when the centralized part of the network is given the control on all the routing operations. However leveraging the infrastructure can result in signalling overhead and may not provide optimal routes. A trade-off should be found between overhead and routes optimality. The characteristics of the different hybrid wireless networks should also be considered in the routing approach, due, for example, to the different types of mobility in each network.

5. An integrated and dynamic architectural model

From our investigation in this area, we believe that it is essential to mutually benefit from the different hybrid architectures. This can be fulfilled via integrating today specific and static (Intra, Inter or extra cellular) architectures in a dynamic and opportunistic hybrid wireless architecture. This integrated architecture depends on each MN situation and traffic conditions. Making use of the ad hoc network potential, the expected benefits are enhancing performance (maximum throughput, minimum delays), extending infrastructures zones, load balancing and/or aggregating separate resources into a grid of resources.

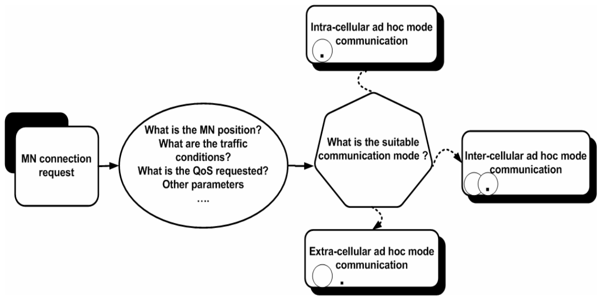

Figure 8: Dynamic and opportunistic communication mode

Although the expected benefits, a sort of heterogeneous environment is created that requires Inter-technological solutions. This may pose some restrictions to network operators and/or service providers, due to the need to providing: mobility and ubiquity, convergence and inter operability between different systems, security and confidentiality that may be between different operators. Also, broadband connectivity may be a necessary requirement. For successful deployment of such type of architectures, some important points should be satisfied, which are: acceptability of the deployed system as well as the offered services by the clients, simplicity of deployment and compatibility with the existing architectures, security and efficient AAA mechanisms extending the existing ones, connectivity quality guaranteeing service continuity, and simple access.

6. Conclusion

As a result of our investigation in this paper, we conclude that hybrid wireless networks are considered as a young research domain, currently taking a lot of attention from the industry and the research community. Most of the work in this area is not yet mature and a lot of efforts are undertaken towards applying these networks within the short term. In this paper, we discussed some of the existing research challenges in hybrid wireless networks, proposing our vision for a potential architectural model. We noticed that an emerging research challenge lies in applying the concept of grid computing within these networks, aggregating the separate mobile resources into a mobile or a fixed grid. Also, security is an important challenge in such environment, where trust should be maintained between heterogeneous networks' elements as well as among fixed and dynamic nodes. Particularly, providing appropriate Authentication, Authorization and Accounting (AAA) is one of the difficult issues that worth more investigation. Moreover, routing represents one of the emerging challenges, where some research contributions presented partial solutions for this problem, without a general solution until now. Based on the discussed challenges, we gave some key requirements towards an architectural model for deploying hybrid wireless networks in a way that serve both users and service providers.

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