Chapter 7

COOPERATION IN AD-HOC NETWORKS

Wireless Multihop Networks from Theory to Practice

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Abstract: In this chapter we are outlining the major challenges encountered when one is trying to deploy realistic ad hoc networks. We are also emphasizing that the current trend towards less mobile mesh networks and sensor networks are actually most probably enabling the emergence of ad hoc type of networks for the civilian markets. Our main focus is to give enough starting points for interested reader to read more specific literature on the existing research in this fast moving field. One of the main conclusions of the chapter is that providing cooperative ad hoc networks requires much more than deploying ad hoc routing capability into network. Especially if one is limited to use IEEE 802.11 technologies, one has to be very careful with the performance limitations. Apart of advocating the

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less-mobile mesh networks, we point out that the recent suggestion to use "multi-radio" approach is a very sensible one. We also speculate on more advanced research possibilities, namely we point out that cognitive radio and networking principles especially, if combined with efficient topology awareness might be an effective way to ensure optimal and cooperative ad hoc networks in the future.

Keywords: cooperation; wireless ad hoc and mesh networks; coloring algorithm; multihop communications

1. Introduction

More than a decade the research community has been quite intensively studying the mobile ad hoc networks, popularly known as MANETs. The great vision since the beginning of their development has been to create autonomous and self-organizing network without any pre-established infrastructure or centralized administration. This enables the randomly distributed nodes to form a temporary functional network and support seamless leaving or joining of nodes.

A tremendous amount of work has been done towards solving research problems related to wireless ad hoc networks (see *e.g.*, [Toh, 2003; Toh, 2001a; Perkins, 2001] and references therein). Although a considerable amount of successful research is done, especially when considering military ad hoc networks, the deployment of *large-scale (massive)* ad hoc networks in the civilian context has been limited to very few cases. There are certainly many reasons for this lack of commercial success, one of those being that the time has not been ripe for ad hoc networking, and certainly many practical engineering problems have been underestimated during the first phase of enthusiasm.

In certain sense all wireless digital communication requires *cooperation* as the systems are required to share resources, and at the very least the end-to-end hosts need to have transmission systems and protocols that are compatible, and somehow standardized. The requirement for cooperation in the case of ad hoc systems, however, is a very stringent one and is present at all system levels. These challenges have not always been foreseen in the right context.

We do not claim to give a comprehensive review on ad hoc networking in this chapter due to fact that it would be out of the scope, and most importantly due to space limitations. There are many excellent treatments available today, and we refer the reader for example to the excellent book by Siva Ram Murthy & Manoj ([Murthy and Manoj, 2004] and reference therein), one should look also other recent reviews (*e.g.*, [Toh, 2001a; Perkins, 2001; Basagni, 2004; Sheu and Jie, W. (Editors), 2005]). This chapter is a quick glance to main issues that one must take in account, when one is designing *multihop, ad hoc* networks.

Our subtitle "from theory to practice" is emphasizing the goal to understand the realistic limitations that we encounter with the present day multihop MANET approaches. One of the key issues is to stress the fact (that was not entirely new insight for the first generation packet network researchers, but has sometimes been not valued enough) that routing itself is not the only problem for multihop wireless ad hoc networks. In fact, for guaranteeing reasonable quality of service, one needs to consider many other aspects than routing, and depending on the chosen transmission and network layer technologies, there are always limits on how many hops and what level of mobility can be supported. This statement is very much a practical engineering based, *i.e.*, regardless of some asymptotic, theoretical limits that are derived on ad hoc capacity, in practice, when one is deploying real systems (at least with the foreseeable technology) there are limits for ad hoc network practicality even in the capacity domain. Due the chosen "practicality" -theme, we are mostly considering only IEEE 802.11 -type of deployment scenarios in our examples. This is done on purpose as most of the practical experimentation is done by using WiFi-systems. However, this is also a limitation of this chapter, which we are wholeheartedly admitting.

In the following, we start with the quick review on some useful historical facts, and also give some framework suggestions for our work. This framework part includes also some definitions and scoping for the "cooperation" itself. We are also commenting some possible interesting research domains that may become more important in the future. After the introduction part, we progress on analyzing the case of multihop wireless ad hoc networks, especially in IEEE 802.11 context. This work is mostly based on the wireless mesh (low mobility) case, and we have chosen to use mostly experimental treatment from our and others' previous research work. Finally, we progress from the multihop capacity work towards some more recent possibilities, such as showing how distributed coloring algorithms and topology control can be used in the wireless ad hoc and mesh context. In the very end, we are drawing some conclusions and dare also to present some longer-term research visions. We are also specifically commenting as requested by editors on possibility to have ad hoc networks as a part of "4G infrastructure" in the future.

Ad Hoc and Sensor Networks Drivers

There are indications that ad hoc networking is finally finding its place, and has also good possibilities to be adopted for commercial purposes, perhaps not as an alternative, but as an extension to existing paradigms. There is on-going interest to apply ad hoc networking principles towards a range of possibilities such as (community) *mesh networking*, *range-extension* of cellular and mesh networks, and small-scale special purpose ad hoc -networks such as Personal Area Networks for games and entertainment. This is in part reflecting the enhanced technological capabilities, but also the fact that real applications cases have been found. This is good, as only slightly over simplifying, a lot of research in the case of ad hoc networking has been almost purely technology push driven.

More recently wireless sensor networks (WSN) have emerged as equally strong research topic, and many of the fundamental problems are shared between "traditional" ad hoc network and WSN research. However, we are emphasizing that WSN research is not a recent spin-off from ad hoc research, as it has a long history in the industrial automation and military domain. In fact, the Distributed Sensor Networks (DSN) program of DARPA (Defense Advanced Research Projects Agency) was launched already around 1980 in the U.S.A.

As mentioned ad hoc networks and wireless sensor networks share many problems (see recent treatments like [Akyildiz et al., 2002; Karl and Willig, 2005]). Specifically problems related to self-configuration, ad hoc routing, and power consumption are shared between these two domains. However, from the drivers of research point of view, there are some differences. Let us oversimplify and somewhat exaggerate. Ad hoc networking research has been more strongly technology push related, and apart from few special cases (such as military networks) there are only a limited number of well-recognized and accepted application cases available to draw system requirements for *commercial systems*. This is also a challenge, when one tries to compare different research proposals and solutions, because without systems level requirements the comparison might become arbitrary at least from the industrial point of view. Overall, it is quite remarkable how little we have real civilian, mass-market wireless ad hoc products available, taking in to account the massive amount of research done.

Wireless Sensor Networks are somewhat different in their status. Although, there is equally strong technology push, especially if one is looking for design on low-power radio technologies and microelectronics, there has been from the beginning a strong emphasis on prototyping. This is probably due to the fact that WSN–research is also closely related to embedded systems development in general that has always been very much application driven. However, many of the current uses of WSNs are very much "on the spot" applications or simple technology-demonstrators, *i.e.*, narrowly chosen to fulfill some specific project and partnership requirements.

Multihop Packet Radio Networks

The requirement to have a cooperative behavior to enable efficient multihop ad hoc networks has been known at least for 30 years. In fact, it might be useful to emphasise that packet radio networking research started around the mid-1970s is a clear precursor of the work done in the ad hoc and multihop context today. The seminal work done by the first generation of packet radio research is still very valuable today. We refer the reader to such contributions as the series of Kleinrock & Tobagi authored articles on packet switching and packet radio networks ([Kleinrock and Tobagi, 1975], [Tobagi and Kleinrock, 1975], [Kleinrock, 1978]), the early packet radio *network* article by Kahn ([Kahn, 1977], see also [Kahn et al., 1978]), spatial reuse paper by Kleinrock & Silvester ([Kleinrock and Silvester, 1987]), and many others (see *e.g.*, [Jubin and Tornow, 1987; Shacham and Westcott, 1987; Tobagi, 1987; Kahn, R. E. (ed.), 1978] just to mention a few).

Cooperation and Challenges

The challenges in the case of ad hoc networking are broadly related to issue to ensure enough cooperation between distinct nodes, and at the same time using the scarce wireless resources efficiently. The *cooperation* is defined as "the action of co-operating, *i.e.* of working together towards the same end, purpose, or effect; joint operation" ([OED, 2001]). In the case of ad hoc networks one should be careful to understand that there are two distinct co-operation domains;

1 *"Communications Cooperation"*, in the strict communications stack domain, means that we need to provide a common set of communications protocols and transmission methods for all the corresponding hosts so that the network can be established. This problem is shared with all communication systems, but the dynamical nature of the ad hoc networks makes this quite difficult. In the case of the ad hoc networks the challenges are rising from the need to support *distributed* algorithms and protocols, and dynamic topology without sacrificing too much of efficiency.

2 *"Social Cooperation"* of the forwarding nodes for a common good is another aspect. There the challenge is the question how to guarantee that nodes between the source and the destination are cooperating on packet forwarding. In the case of the closed ad hoc network applications (such as military or emergency networks) this is easier to ensure than if one is considering highly dynamic privately owned network hosts. This sort of "social cooperation" is beyond the scope of this chapter, but other chapters in this book are addressing at least in part this problem domain. We also note that the recent trends towards community mesh networks, and range-extending, commercial ad hoc applications are also making this problem easier to tackle in this limited domain, that are not as dynamic as full MANETs.

A very large amount of research has been invested towards ad hoc routing. Although there are still some problems to be solved, we mostly comment here certain mature technologies that have emerged. We believe that the major part of the future research work will be directed to new problem domains. In fact, some engineering problems need to be solved even before intelligent link-aware routing solutions can be implemented easily.

From the cooperative behavior point of view clearly more work with MAC (Media Access Control) layer algorithms is required. Most of the current testbeds are using IEEE 802.11 MAC (or slightly modified versions of it). The popularity of 802.11 makes it difficult to envision quick departure from it, but regardless more efficient MAC protocols are required (cf. [Chandra et al., 2000; Murthy and Manoj, 2004]). In the case of WSNs there has been increased activity on designing low-power, low bit-rate MAC solutions for ad hoc networks. The idea of building smart-antenna based MAC-protocols for ad hoc networks has recently gained popularity and can be a promising solution under some certain conditions (see [Ko et al., 2000; Fahmy et al., 2002; Choudhury et al., 2002; Ramanathan et al., 2005; Vilzmann et al., 2005], see also survey by Vilzmann & Bettstetter, [Vilzmann and Bettstetter, 2005]). Power control, especially when related to *topology control*, is another important research challenge that has been gaining a merited interest (see [Santi, 2005] and references therein).

Finally, we mention in this introductional part that energy efficiency is still a challenge to be met, and it is very demanding problems as it requires cross-layer optimization approach, including also careful design of underlying electronics itself.

Cooperation Domains and Metrics

The challenge with the cooperative networks is that even in the case of communication cooperation there are different domains of cooperation. The domains, in fact, rise quite naturally from the fact that there are disjoint resources that need to be shared between hosts. These include most notably need to share *frequency, time* and quite often *space*[1].

Apart from the need to share resources in cooperative manner, there is also an issue of relevant **metrics**. Some of the metrics are related to physical resources, most notably to available energy. Other metrics are typically related to communication domain itself (*e.g.* bit-rate, latency, ...). Designing and operating an efficient ad hoc network is fundamentally a dynamical *optimization problem*. As the ad hoc network itself can be relatively dynamic, the system itself must be able to adapt to changes (and this certainly goes beyond "simple" routing). However, in order to make optimization decisions one needs to have a performance metric. This is a difficulty, as in the end any reasonable ad hoc metric would be a multivariate and multiparameter function. Moreover, as the decisions should be done in the distributed fashion it is not always clear how to guarantee global convergence or fairness. In fact, one has to remember that although we talk about cooperative system, different users ("players" in a game theoretical sense) can have highly different goals, hence different performance metrics. Although the performance of computer networks have been studied for decades, the issue of highly distributed performance optimization in the case of ad hoc networks still needs more fundamental research before we really understand all the limitations.

One of our own recent contributions on the discussion is to point out that ad hoc cooperation is not only optimization and game modelling problem, but it is also policy optimization issue. Policy optimization here means that as the system will inevitably encounter situations, where mutually exclusive optimization issues and race-conditions occur, there needs to be a way to describe policies or preferences on how to solve such situations. Apart from some recent work done in the case of spectrum agility (cognitive radios), and some relevant analysis with BGP and software radio work, as far as we are aware of the ad hoc "policy languages" have not really been considered in depth.

2. Limits of Multihop

MANETs find their applications mostly in multihop scenarios where there is no wired infrastructure available. The envisioned applications of ad hoc communication include commercial and educational use, emergency cases, on road vehicle networks, military communication, sensor networks, etc. However, many analytical and practical studies have already shown various drawbacks of multihop ad hoc communications (both technological and human limitations) in terms of throughput, fairness, energy and bandwidth limitations, which make it difficult to envisage commercial deployment of very large ad hoc networks.

Although stand-alone ad hoc networks might provide support for interesting applications, they have not really taken up outside military domain. While the presently deployed hotspots offer only single hop connection to the infrastructure these wireless multihop technologies can be leveraged to increase the reach of such networks. This can be accomplished without wired infrastructure in several ways. On one hand ad hoc routing among clients can increase the coverage area of an access point and on the other hand a wireless mesh network can be established to interconnect APs. The combination of multihop wireless networks with fixed/cellular networks seems very attractive, because it allows usage of even wider range of services. However, it is *not* without its practical limitations.

In the next sections we will walk through several issues that characterize the ad hoc multihop networks and discuss their performance taking into account a large number of analytical and practical studies carried out both in the industry and academia in the past decade.

Routing Metrics Challenge

Since the ad hoc network is a cooperative set of mobile nodes, each node plays a role of a logical router and forwards packets from other nodes. Due to the dynamic nature of the ad hoc networks, highly adaptive routing protocols are required to cope with the frequent topology changes. There has been a substantial work done in the ad hoc routing resulting in design of number of different MANET routing protocols such as DSR ([Johanson et al., 2001]), AODV ([Perkins and Royer, 1999]), DSDV ([Perkins and Watson, 1994]), OLSR ([Clausen et al., 2001]) etc. Depending on the technique of acquiring the route to the destination, the existing ad hoc routing protocols can be divided into three groups (see also [Feeney, 1999] for further discussion on the taxonomy of routing protocols). *Reactive* protocols acquire and maintain the routes in an on-demand fashion and/or the route discovery is initiated only when needed. Examples of reactive protocols include DSR and AODV. *Proactive* routing protocols, on the other hand, maintain the routes to all destinations in the network constantly. OLSR is a typical example of a proactive routing protocol. *Hybrid* routing protocols are both reactive and proactive in nature. The protocols allow the nearby nodes, grouped into zones, clusters or trees, to maintain the routes pro-actively and discover the routes to the far away nodes in reactive manner. ZRP ([Haas and Pearlman, 2001]), is one of the most known belonging to this group of protocols. Recently there has been also interest on how to use extended OSPF in the wireless, ad hoc context (see [Ahrenholz et al., 2005]).

The routing in MANETs has traditionally focused on finding out solutions that minimize hop-count and provide fast adaptation in the case of highly dynamic (mobile) networks. One of the problems with the most minimal hop-count approaches is that it does not take the link-quality into account . Especially in the case of IEEE 802.11 based networks that are deployed into large area, the difference between link qualities can be very large indeed. As a result, it is not rare case that the minimum hop-count based routing schemes chose routes with significantly less capacity than the high-quality paths available in the network. This issue has been pointed out in details, *e.g.* by [De Couto et al., 2002].

A number of different performance metrics, such as the ETX in [Couto et al., 2003] (expected transmission count metric), per-hop RTT ([Adya et al., 2004]), link-quality dual (SNR, BER), and per-hop packet-pair ([Draves et al., 2004]), that characterize the quality of the wireless link have emerged in the recent years. For example, ETX finds high-throughput paths using per-link measurements of the packet loss in both directions of the wireless links. In the per-hop RTT approach, the nodes probe periodically their neigbours measuring the RTT. The RTT samples are averaged using TCP-like low-pass filter and the path with the least sum of RTT is selected. The per-hop packet-pair technique, on the other hand, uses two two-back-to-back periodic probings to the each neigbour. The receiving node measures the arrival delay between the two probes and reports it back to the sender. The sender averages the delay samples and the finally the route with the least delay is chosen. Both the per-hop RTT and the PckPair metric implicitly take into account the load, the bandwidth and the loss rate of the wireless link. One problem related to link-quality aware routing is the practical issue, how to actually measure some of the lower-layer (MAC and PHY) parameters and use them at the upper layers (e.g network layer). We discuss this problem in more detail below.

Energy Consumption in Multihop

The nodes in a mobile ad hoc network rely on batteries for proper operation. Since they need to relay their messages through other nodes toward their intended destinations, depletion of the batteries will have a great impact on the overall network performance. Especially if the power consumption rate is not evenly distributed across all nodes, some nodes may expire sooner than others leading to partitioning of the network ([Toh, 2001b]).

Increasing the lifetime of each node is a rather complex process and can be done at different layers. The so-called non-communication power consumption is very dependent upon the actual hardware implementation. Further on an adaptive power control at the physical layer can help to conserve the battery life of the hosts. On the other hand, data link and routing protocol design can also significantly impact the processing and the transceiver power dissipated in wireless communication. At the data link layer, energy conservation can be achieved by using effective retransmission schemes. To maximize the lifetime of an ad hoc network, the routing protocols could introduce sleep periods so that the hosts can stop transmitting and/or receiving for arbitrary periods of time without causing any serious consequences in the network operation. Moreover, transmission power can he used as a routing metric.

When talking about conserving the life of the battery in the ad hoc networks it is maybe necessary to mention the well known myth saying that the multihop communication *always* saves energy. Seen from the prospective of pure radio propagation theory, the power necessary to transmit a bit of information over a radio is proportional to the distance. If we introduce a multihop communication between two nodes, there should be less power needed to transmit over shorter distances. However, in order to avoid misleading results, particular care should be taken that the energy efficient communication protocols are designed around accurate energy models of the used hardware. In such case, multihop can save energy only if the path attenuation dominates the energy consumption of the hardware which is far less probable then believed ([Min and Chandrakasan, 2003]).

TCP/UDP over Multihop 802.11

In a large number of recent studies on ad hoc networks and specially WLANs, the authors have studied the performance of TCP over IEEE 802.11. The "misbehaviour" of TCP over wireless is a consequence of several issues, and is well recognized problem (see, for example, [Fu et al., 2003; Gurtov and Floyd, 2004; Xylomenos et al., 2001]). The main reason for the unsatisfactory performance of the protocol is the fact that TCP has been primarily designed for wireline networks, where the channel error rates are very low and the congestion is the main cause for packet loss. As a result, there have been several approaches how to optimize TCP for wireless networks. For more details the reader is referred to [DeSimone et al., 1993; Balakrishnan et al., 1995; Sinha et al., 2002]. There has been also number of studies that aim to final optimal parameter values for TCP over wireless systems; the parameter set typically includes, *e.g.*, packet size, congestion window size and buffer size.

In the following we highlight the most common anomalies of TCP in the mobile ad hoc networks. First, due to the dynamic nature of the topology of the ad hoc network some of the wireless links can break. As a result, TCP may experience timeouts that will seriously impact the performance. Moreover the fact that in the wireless network a packet can be lost not only due to congestion but also because of the errors in the wireless channel, leads to undesired TCP behaviour. Additional losses and transmission errors can be caused also by a hidden terminal in the network. Anyhow, regardless of the loss nature, TCP will incorrectly interpret it as a sign of congestion, which will cause adaptation of its window size and reduction of the data flow. Several efficient mechanisms have been proposed in the literature for improving the TCP performance in wireless ad hoc networks ([Bakshi et al., 1996; Xylomenos et al., 2001]). Second, it is shown that TCP performance in an ad hoc multihop environment is sensitive to different parameters such as packet size and TCP window size ([Fu et al., 2003]). Several measurement studies has verified that for a specific network topology and traffic flow, there is a TCP window size at which the throughput reaches the highest value. Further increase of the window size does not lead to a better result. Finally, degradation of the network performance caused due to the interaction with the IEEE 802.11 MAC protocol. More specifically, the present IEEE 802.11 MAC protocol may cause unfairness between competing TCP traffic flows, and a capture of the whole wireless channel by a single node can occur relatively easily.

Performance of Ad Hoc Networks Based on Measurements

Most of the research studies tackling mobile ad hoc networks are based on simulations. However, the simulation results not always reflect the real scenario and can only give a good approximation of the simulated environment. That is why measurements obtained from real hardware testbeds are always recommended and welcome. In order to illustrate some of the challenges and the performance limitations a simple multihop network has, we present here only a small part of results from a comprehensive set of measurements that we carried out in the past couple of years.

A common way to quickly estimate the performance of a specific wireless network is to measure the most common parameters such as throughput and delay. By throughput we mean the actual transport layer payload without any headers successfully received per second. In this section we shall give a quick look into some performance issues of a simple ad hoc network based on measurements and simulations. Here we shall analyze what is the TCP and UDP throughput to be expected in a homogeneous 802.11a/b/g multihop setup. We also give an overview of the outcome from the throughput measurements in a heterogeneous 802.11b, 802.11g and Bluetooth environment.

The measurement setup in the multihop case is a simple string topology in office environment. All measurements were performed using laptops in a Linux environment and TCP NewReno with selective acknowledgement and enabled timestamps. Although we are sure that the tested system could benefit from different protocol boosters or TCP modifications, we are leaving them strictly out from our study. We were limiting our measurement campaign to unmodified, off-the-shelf solutions, since these are building blocks that are mostly used in testbeds, community networks, and simulation studies.The simulation results given in some of the figures are performed using the network simulator ns-2.

On figure 7.1 both measurement and simulation results of a TCP/UDP throughput as a function of a number of hops are depicted. Having in mind the shortcomings of ns-2, we improved the 802.11 MAC module and included enhanced error modelling. The reader is referred to [Wellens et al., 2005] for further details.

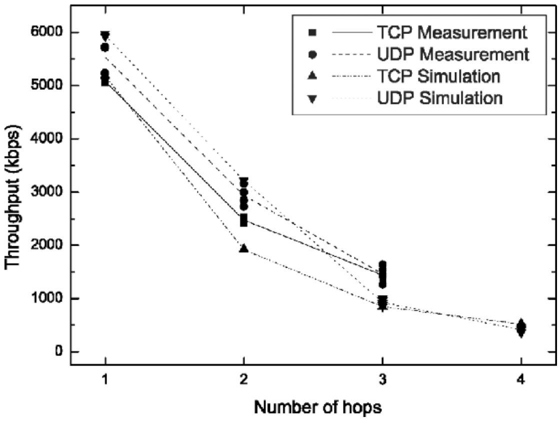

Figure 7.1. TCP/UDP multihop throughput measurements and simulations.

The figure clearly indicates that large number of wireless hops, in a single-radio per node case, is very inefficient, as throughput is lost rapidly. This is unavoidable even in the perfect environment without transmission errors, delays, etc., as it is inherent for single radio repeaters. It is even more serious in the realistic Wi-Fi multihop environment. One can notice that already three hops is quite suboptimal for many purposes. Further increasing of the number of hops will result in unacceptably low throughput. In our tests there were no external nodes contending for the channel. At a public hot spot other users will also produce interference, so the end throughput would fluctuate more.

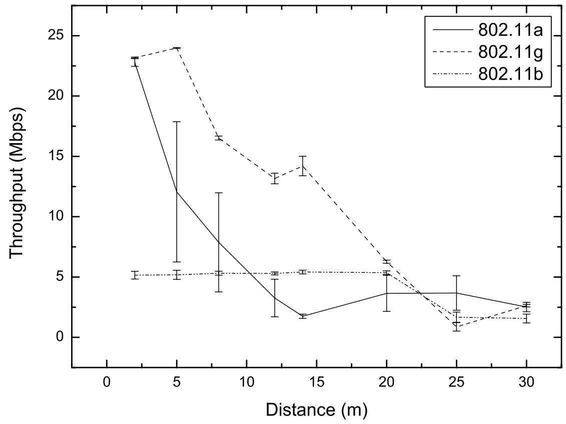

Figure 7.2. TCP throughput measured with 802.11a, 802.11b and 802.11g.

In order to answer the uncertainty on how 802.11a compares to 802.11g, we measured the throughput of 802.11a and 802.11g technologies in a real indoor environment. Both technologies are quite similar on PHY layer but use different frequencies. Figure 7.2 shows the TCP throughput of 802.11a, 802.11b, and 802.11g as a function of distance. We can identify three segments in the graph: at short distances with LoS (line of sight), as expected, both technologies reach the same maximum throughput of about 23 Mbps. When the nodes are further away from each other (>20 m), with obstacles in between, both technologies adapt their bit rate to the lowest possible to maintain the connection. In the range in between, the throughput of 802.11g clearly outperforms 802.11a. Due to the higher path loss of 802.11a, the physical layer mode switches to more robust modulation and coding which leads to lower bit rate at the distance of 5 meters LoS.

Recently the number of different wireless and radio technologies has increased dramatically. These diversity will require efficient interworking of technologies for the deployment of the future wireless heterogeneous systems. In this occasion we address the impact of heterogeneity on the performance of a network, comprised of radios which operate both in the 2.4 and 5 GHz ISM bands. We opted for a three-hop connection consisting of BT, 802.11b, and 802.11g links. It is obvious that the BT link a the bottleneck in the network. Figure 7.3 shows the TCP throughput both over the described three-hop configuration and over a single BT-link. We see that the performance degradation due to multihop is rather acceptable. In general, the heterogeneous multihop connections are more or less limited to the performance of the slowest link involved. This behaviour limits the usability and the applications of such networks. However, having heterogeneous connections in the network can be used to, *e.g.*, extend the range of BT or interconnect technologies.

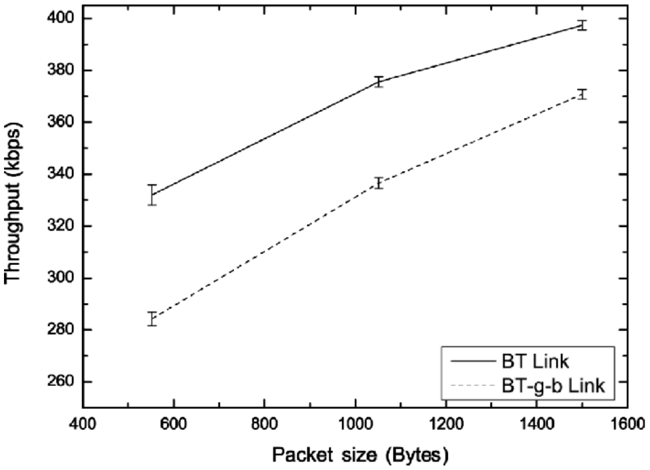

Figure 7.3. Comparison of a single BT link and a heterogeneous 3-hop connection consisting of BT, 802.11g and 802.11b.

Multiradio Approach

We already discussed, in the previous sections, some of the key limitations in the ad hoc multihop wireless networks. Number of them are rising from the MAC-layer or the IEEE 802.11 physical layers themselves. However, not all of those limitations require design of new radios or modifications to MAC-layer. Our practical experimentation and relatively trivial theoretical considerations indicate that the key challenges are mainly related to heterogeneity, interference and collision avoidance. Moreover, due to usage of a single radio for forwarding the traffic the existing bit rate will be halved even in the ideal condition without *e.g.* buffering and scheduling overheads. Anyhow, the above challenges are partially interrelated, and we believe that they could be tackled by enabling "multi-radio" concepts. Emphasizing the need of *multiradio* approach is, surprisingly, quite rare in the ad hoc research literature. The main proponent with very interesting and high quality results on the benefits of using multiple radios has been the Microsoft Research Networking Research Group (see, for example, [Bahl et al., 2004]).

The multi-radio concept means that the wireless nodes could have more than one radio NIC (Network Interface Card) available. In the case of heterogeneous networks this is natural, but we point out that even in the single technology there will be benefits if the nodes have, for example, one radio for receiving and one for sending. The simultaneous use of the radio interfaces, operating on different channels, will boost the performance of the multihop network by minimizing the delay in the data transmission. Multiple interfaces could be also useful for minimizing the handoff latency in the WLANs. However, this is easier to stipulate than to do due to a number of technological problems. One issue is to provide robust software to ensure cooperation and bridging between radio cards. The state of the art in this field is still far from perfect. One major problem is to provide auto-configurability in order to manage co-channel interference between radios. For example in the case of 802.11b cards, two cards would be virtually useless if both were to use same frequency band for their operation.

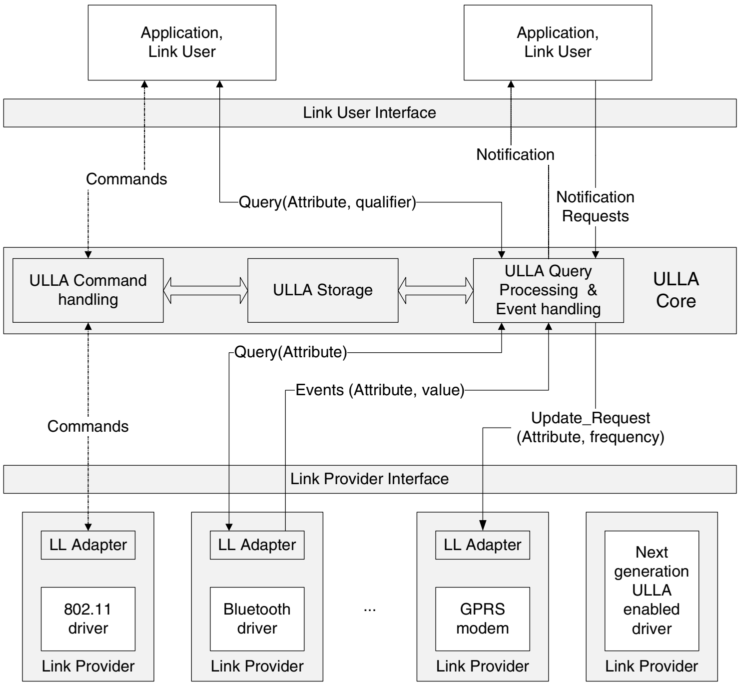

Figure 7.4. The architecture of the unified link-layer API.

Another major problem in realizing any of these multiradio approaches is the difficulty of programming in relation to several wireless technologies. In present-day operating systems the interfaces used to access wireless LAN network interfaces are completely different compared to Bluetooth ones, for example. Additionally, existing programming interfaces offer no useful abstraction of the different attributes and parameters characterising wireless technologies, thus requiring rather intimate understanding of the technology in question from the programmer. One solution to these problems is the *Universal Link-Layer API*, or ULLA for short, that is being developed in the European *GOLLUM*-project ([Farnham et al., 2005]). In addition to offering a unified interface towards different link technologies, the ULLA supports setting up different types of asynchronous notifications on changes in link conditions, and collection of statistical information on the conditions of wireless channels. Figure 7.4 illustrates the overall ULLA architecture.

This kind of API will obviously make implementation of multi-radio, link-aware routing protocols considerably easier than it is today. The work in the GOLLUM project is also very practise-oriented, and early reference implementations of the API have already been developed. Several exiting possibilities for applying this API are being explored at present, especially in relation to combining cellular network connections with more traditional technologies, such as IEEE 802.11, that are often used in the ad hoc community. We definitely see ULLA as very powerful enabling technology for link-aware ad hoc routing protocols and multiradio approaches. More details on the GOLLUM architecture design can be found from [Farnham et al., 2005].

3. Spectrum Cooperation

With the exception of multiradio issues, in the previous section we discussed classical Ad-Hoc networks in which all nodes utilize the same channel to communicate with each other. It is intuitively clear that this leads to highly inefficient use of the radio spectrum, and thus yields suboptimal capacity for end-to-end connections, especially in dense networks with considerable amount of offered traffic. In this section we shall have a look at mechanisms using which nodes in Ad-Hoc networks can also cooperate in the frequency domain[2].

We shall begin by considering a graph-theoretic approach we originally suggested in [Riihijärvi et al., 2005] as a solution to frequency allocation problems in infrastructure-mode wireless LANs. The scheme is based on the solving of the graph coloring problem on an approximation of an *interference graph*, a concept well known in frequency assignment problems. We discuss two variations of the approach. We focus on the one suitable for assigning frequencies for clusters of nodes, and discuss briefly modifications and extensions for per-connection assignments. Naturally, these approaches can be combined in case of traditional clustering algorithms are used, as first scheme can be used amongst clusters, and second one to establish communications between cluster heads.

Let us begin by considering a collection V of nodes amongst which set of frequencies F has to be assigned by some function $f : V \to F$. We shall for the moment assume that the frequencies corresponding to elements of the set F are non-overlapping, a restriction we shall remove later. With this assumption, it suffices to assign frequencies to nodes with the constraint that two nodes are assigned different frequencies if they would interfere with each others' transmissions if this was not done. We can formalise the interference relation as the *interference graph* $G = (V, E)$, where $\{v, w\} \in E$ if and only if $v \in V$ and $w \in V$ would interfere if $f(v) = f(w)$. Formulated in this manner, the frequency assignment problem becomes the classical graph colouring problem with colour set F and colouring f (see, for example, [Diestel, 2000] for references and more detailed discussion).

Solving the graph colouring problem exactly is well-known to be NP-hard, and thus takes exponentially increasing time as the number of nodes is increased. Due to this, the colouring approach has mainly been applied in frequency planning of cellular systems, to arrive at static or rarely changing frequency allocations. For a review of this work, see [Eisenblätter et al., 2002] and references therein. Nevertheless, effective heuristics make it possible to apply these techniques dynamically, even on nodes with limited processing power. Particularly appropriate is the "degree of saturation" heuristic proposed in [Brélaz, 1979], as it has attractive scaling properties, running in $O(|E| \log |V|)$ time, and is still among the best known heuristics for colouring *geometric graphs*[3].

The DSATUR heuristic is a greedy algorithm based on *degree of saturation*. The degree of saturation for a vertex v is defined as the number of different colours already used to colour vertices in its ("one-hop") neighbourhood $\gamma(v)$. The vertex degree calculated from the uncoloured vertices can be used to break the ties. More formally, the DSATUR algorithm can be described in terms of the following pseudocode, following [Buckley and Lewinter, 2002]. The algorithm takes as an input the set of uncoloured vertices U, the neighbourhood structure of the graph, and the total number of vertices.

```
DSATUR ($U$, $\gamma(v)$ $\forall v \in U$, $N$) {
  Sort $U$ from largest to smallest degree
  Colour first vertex $v$ of $U$ by $1$
  $i := 1$
  Delete $v$ from $U$
  while ($i < N$) {
    $j := 1$
    found := "no"
    Select first $w$ from $U$ with maximum degree of saturation
    while (found = "no") {
```

```
        if (Some $x \in \gamma(w)$ has colour $j$)
          $j := j + 1$
        else
          found := "yes"
          Colour $w$ by $j$
          $i := i + 1$
          Remove $w$ from $U$
      }
    }
  All done; Output the colouring
}
```

For more comprehensive discussion on DSATUR performance, and for some proposed variations to the basic algorithm, we refer reader to [Turner, 1988] and [Battiti et al., 2001].

To give an example of this scheme, consider the left panel of figure 7.5, illustrating the interference graph of a small wireless network in a typical office environment. The interference graph is shared amongst the nodes (we discuss the practical problems and corresponding solutions related to this process below), which then all apply the DSATUR algorithm. Initially, the degree of saturation of all nodes is zero, so the node with the highest degree is coloured in greedy manner, and is assigned the first frequency from F. Now all the uncoloured nodes have degree of saturation of one, so degree is again used to break the tie for assigning the second frequency to the node on lower-right corner of the map. As the two of the nodes have degree of two, additional tie-break rule is required on the third round of the algorithm. Simplest solution is to use the MAC-address of the nodes interpreted as 48-bit integer for this. These two nodes are then coloured on successive rounds, both assigned the third frequency, and finally the remaining node of degree one is coloured. The right panel of figure 7.5 illustrates the resulting "cell structure".

In the clustered and infrastructure cases, this simple scheme turns out to result in good channel assignments. We expect more refined applications of similar techniques to surface, where more information about the wireless network is encoded into the model graph. This would enable more refined optimizations, including consideration of the propagation environments in different channels, and inclusion of dynamic characteristics of the wireless environment into consideration. For frequency assignments between individual nodes variations of this scheme must be considered. In the graph-theoretical framework *edge colourings* and *matching problems* are two of the appropriate tools in this context. For an example application of edge colouring into channel allocation, see [Gandham et al., 2005].

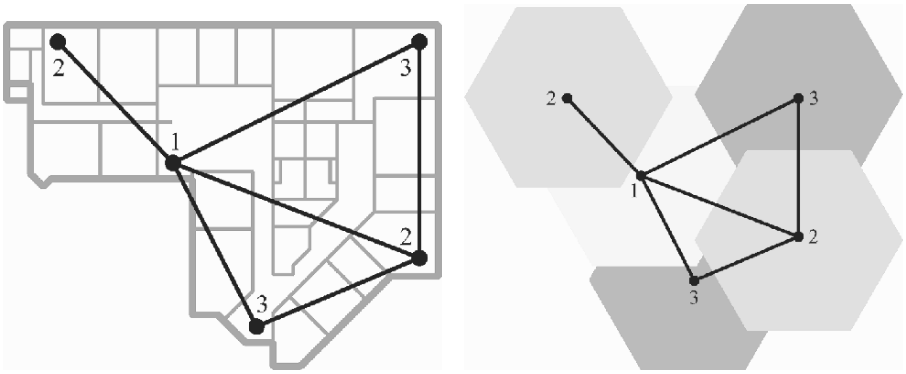

Figure 7.5. An example of a four-node wireless network, with the interference graph together with the values assigned by the colouring algorithm on the left, and illustration of the resulting "cell structure" on the right.

Two variations of the classical colouring problem often considered in the frequency allocation context are the on-line colouring problem, and T-colouring. As the name suggests, in on-line colouring the vertices are presented to the algorithm sequentially, and it must irrevocably colour those vertices without knowing the future inputs. The main application of these types of on-line colouring algorithms is to assign frequencies to nodes or clusters while retaining the existing allocations. The theoretical performance bounds of on-line algorithms tend to be poor, forcing the use of regular algorithms in occasion to optimize the frequency allocations network-wide. For more references on performance of on-line algorithms and example applications to wireless networks see [Halldórsson and Szegedy, 1992] and [Tsai et al., 2002], respectively.

The T-colouring algorithms can be used if the assumption of non-interfering adjacent channels is dropped. More precisely, the definition of a proper colouring is changed to include the condition $|f(v) - f(w)| \notin T$, where v and w are adjacent vertices in the interference graph, and T is a set of integers. If $T = \{0\}$, T-colouring reduces to classical graph colouring. As suggested in the seminal paper of [Hale, 1980], the structure of the set T can be used to put constraints barring use of "too adjacent" channels in nearby nodes. For a review of basic variants of the T-colouring problem, see also [Roberts, 1991].

Another practical problem surfaces if the colouring algorithm returns a colouring using too many frequencies. This indicates that a frequency allocation completely without interference cannot be achieved, at least using the particular heuristic. The most straightforward solution is to apply a graph transform trimming away some of the edges of the interference graph, thus reducing the chromatic index. If the edges of the interference graph carry weights, this trimming can simply be done in the order of least severe interference.

Construction of the interference graph in collaborative manner is also not entirely straightforward. Typical approximation is not to use the connectivity graph of the network instead, even though this disregards any hidden terminal-type of problems that might result. Thus the connectivity graph should be supplemented with additional interference information, if possible. Using fully distributed colouring algorithms, such as one presented in [Hedetniemi et al., 2003], avoids the communication overhead required to explicitly obtain the connectivity information at every node, but the price to be paid is the long convergence time. We do not expect algorithms of this type to be usable in mobile Ad Hoc networks, but they might be practical in some fairly static mesh networks.

Spectrum Agile “Cognitive Radios”

A small note is warranted also on the spectrum agile radios, which are also often called as *cognitive radios*, although Mitola’s original cognitive radio definition goes beyond a simple dynamic spectrum allocation (see [Mitola, 2000]). In principle, the general idea of the dynamic spectrum management is to see a large part of the spectrum domain available for the cooperative use within some predefined policies (see, for example, [Buddhikot et al., 2005] and references therein). This has lead to some highly interesting recent R&D activities, where the issue has been to study, if the primary licensee spectrum domains (*e.g.*, TV-bands) could be used by secondary users in opportunistic manners. One of the best known approaches has been DARPA funded spectrum policy language project XG ([DARPA XG Working Group, 2003]) and IEEE 802.22 ([IEEE 802.22 WRAN WG, 2005]) that is developing a standard for cognitive radio - based air-interface for utilizing unused spectrum in TV broadcasting bands. The work done in the domain of dynamic spectrum management may have a large impact for ad hoc networking, *if* efficient spectrum management mechanisms can be defined the actual deployed systems would benefit from technologies developed by ad hoc research community. In fact, it is highly possible that dynamic spectrum management could be a crucial enabling technology to make ad hoc and mesh networks commercially more interesting and viable.

4. Topology Aware Ad Hoc Networks

As we have already discussed above, topology control has surfaced as a very active research area in ad hoc and sensor networks. We distinguish here two highly prominent subfields, namely *clustering research* and traditional *topology control*, which we understand to mean the tuning of the transmit power of nodes (possibly in combination with smart antennae) to optimize the network structure with respect to some metric of interest. Typical objective is to minimize the energy consumption of the network as a whole.

In clustering protocols nodes are organized into groups, and the “leader” of each group, the *cluster head*, is responsible for management of the cluster. Immediate power savings are possible by, for example, using a simple time division scheme, with the cluster head assigning activity schedules. This way other nodes can remain in sleep mode, turning off unnecessary parts of their circuitry, large portion of the time. Since pre-assigning the cluster heads as part of the network configuration process is obviously unfeasible, some form of automation must be applied. Several proposals have appeared in the literature on algorithms for automatically selecting the cluster heads, see, for example, [Karl and Willig, 2005] and references therein. For evening out the energy consumption, the responsibility for being a cluster head should be rotated amongst the nodes as time passes. Further important requirements on the clustering process are uniform distribution of cluster heads amongst the node population, and uniform distribution of energy consumed.

Classical topology control, on the other hand, deals with configuration of the radio coverages of the network nodes. Perhaps the most well-known classical problem in this domain is the *range assignment problem* and its variants. In these problems a simplified radio propagation model is assumed (such as circular radio coverage of tunable radius), and the coverages of the nodes is tuned to make the network connected with minimal overall coverage areas. If power consumption is taken to be dominated by the power-law attenuation, these kinds of problems would be equivalent to finding the radio configuration that minimizes overall power consumption. However, as we pointed out above, this assumption does not always hold. Thus, care should be taken when applying classical topology control research results on real networks. For a thorough review on these matters, and also on discussion on the problems involved, we refer the reader to [Santi, 2005] and references therein.

We shall now turn from describing and analyzing the state-of-the-art toward discussing likely future developments. Main theme in this section is enabling of network self-organization and optimization using more advanced topology control techniques. We will argue that development of new network abstractions becomes necessary, especially for including the effects of geometric relations of nodes in wireless networks.

A very likely short-term trend is that of improved understanding of the effects of topological dynamics (such as preferential attachment processes) on various network types. Also the spectrum of useful probabilistic graph abstractions is likely to grow. Although there exists models that exhibit the small world, scale-free and rich-club properties familiar from fixed networks, it is still too early to claim that these models capture all the intricacies of especially wireless communication networks at the necessary level of detail. An example of a recent model with these properties is given in [Li et al., 2004], where the appropriateness and precise definitions of these abstractions is also discussed in depth. An important piece of the puzzle that must be put into place before these findings can be used in building self-organizing and self-optimizing networks is the mapping of the efficiency of different protocols into topological characteristics. Some of these mappings are already established, or are trivial to derive, like the signaling and computational overhead of different routing protocols as the function of network topology. This research on network topologies will most probably lead to several surprising insights, like issues related to self-similarity transformed our view on how traffic behaves in networks.

When we have solved the research problems outlined above, autonomic optimization of network operation via topological tuning beyond "simple" power control becomes possible. Network nodes can gather information about the network topology and the protocols being used in the network, and map that information into optimization decisions that can be carried out by changing the network topology. At present, network layer topology can be changed by adapting the routing tables, while different overlay networks already have tunable elements in their topology formation. Another interesting aspect that has only been studied a little is the effect of cross-layer correlations in network topology on the performance of various network overlays and hierarchies.

To enable these kinds of optimization mechanisms based on topology control, we need to develop ways to exchange topology information. Routing protocols already do this on the detailed level. However, for scalability and overhead reasons it might be better to apply suitable network abstractions here as well, and exchange information like average path length, or the exponent related to scale-free degree distribution.

We expect topological optimization to become highly active research area especially in the peer-to-peer networking context but also in wireless ad hoc and mesh networks. Instead of a simple shortest path routing the topology formation takes place under numerous constraints (such as collaboration levels, reputation, reliability and energy considerations, and topology of the underlay), reminiscent of policy based routing. In some peer-to-peer environments economical considerations should also be included into considerations. This is also important observation in the fixed domain, where population densities and economic forces can drive the evolution of the network. However, due to limitations in scope, and especially due to lack of space, we shall not discuss these highly interesting issues in detail. At higher abstraction level, there has already been interesting work (see, for example, [Felegyhazi et al., 2003]) related to ad hoc network self-organization and stability in presence of different user behaviors (from cooperating to free-riding), and we expect further exiting research to emerge from this area.

Inclusion of Geometry

In wireless networks topology at any given layer becomes a secondary quantity. It is mainly constrained by the geometry of the network, that is, the spatial relations of the nodes and their environment and, of course, the dynamics of those. No equivalent of the topological abstractions discussed earlier has arisen for describing wireless networks, save for simple lattice or cellular models, and uniformly distributed point fields often used in simulations.

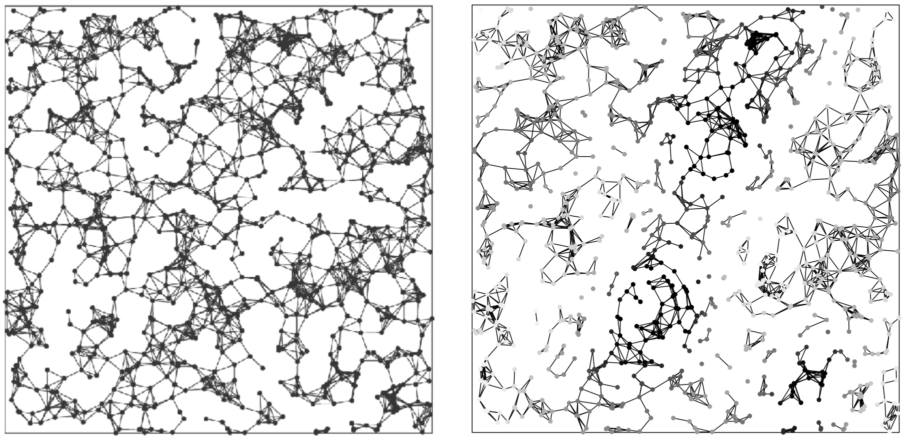

Figure 7.6. A geometric graph modeling an Ad Hoc network with uniformly distributed nodes in flat and curved terrain.

Generic mathematical frameworks such as the random geometric graphs that are suitable for basic analysis of connectivity graphs have been of course developed, see, for example, [Penrose, 2003]. Random geometric graphs are formed by placing nodes on a suitable chosen space, and connected if their distance is small enough. In Figure 7.6 simple model of this type is illustrated, with nodes placed on both flat plane, and on a surface of varying curvature, modeling terrain shapes in hilly or mountainous environments. The difference in the connectivity graphs in these two scenarios is obviously dramatic. Similar differences can easily arise from different mobility patterns of nodes, and also in the fixed network domain from various constraints placed on the network topologies (based again on, for example, trust relationships). Random geometric graphs are, of course, a very simple abstraction, and more refined models will emerge. These will be based at least on correlations in node locations, and on tools of stochastic geometry, see, *e.g.*, [Baccelli et al., 1997].

We expect the models and abstractions of wireless networks to be significantly more complicated than the purely topological models of fixed networks. This is a direct consequence of the complex phenomena wireless communication is associated with. However, significant optimization and self-organization

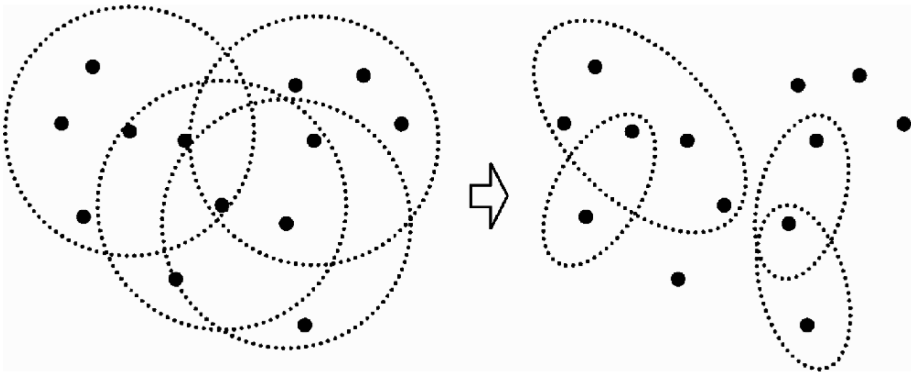

Figure 7.7. Using directional antennae in Ad Hoc networks for interference minimization and topology control.

work can already be done with simple models, such as the geometric graphs discussed above.

As an example, one can consider ad hoc and mesh networks, where adaptive and directional antennae can be used to enhance reliability and minimize interference, see Figure 7.7 for an illustration. The geometrical and topological information plays here a very crucial role. If nodes have information on, at least, their local topology the beam formation and sectorization can be planned much more efficiently and in self-organizing fashion. Especially in the case of unmanaged mesh networks this provides a tempting possibility. There remains also some practical issues, *e.g.* topology and geolocation sharing protocols and "markup" languages need to be standardized.

In the peer-to-peer domain there exists already a number of algorithms and protocols that use information about the underlying topology for optimizing the structure of the overlays they employ, and search processes conducted in the overlay. Similar kind of topology-aware approach can be used to enhance the performance of other types of discovery processes as well, such as capability and resource discoveries in wireless networks. This approach suits particularly well for protocols based on probabilistic and epidemic communications. The key idea here, especially in the resource limited wireless networks is to save resources by trying to send service discovery queries towards "information rich" pointers. Moreover, the abstraction allows to try to send certain queries towards more powerful nodes with fixed communication capability. The issue of self-organization becomes important here since we would like to ensure through self-organization that "richly connected" information nodes are available in suitable places. Hence, self-organization is not only a question of simply organizing communication capability, but to also make some topology control and service location optimization.

Another rich research field is that of dynamical properties related to geometry. It has been well established that many of the mobility models available in modern network simulators are not really satisfactory, and that the choice of mobility model can have a large impact on simulation results. For a well-known, but effective illustration on the differences between mobility models see Figure 7.8. However, the validation of the models is a difficult problem, due to scarcity of user mobility data available. In the practical self-organization design the awareness of mobility abstraction is a useful concept. If different components in the network, *e.g.* ad hoc network nodes, can be aware what sort of mobility is in average occurring around them, they can adapt their self-organization and protocol parameters accordingly. This would lead to self-organizing network, which will adapt based on conceived mobility.

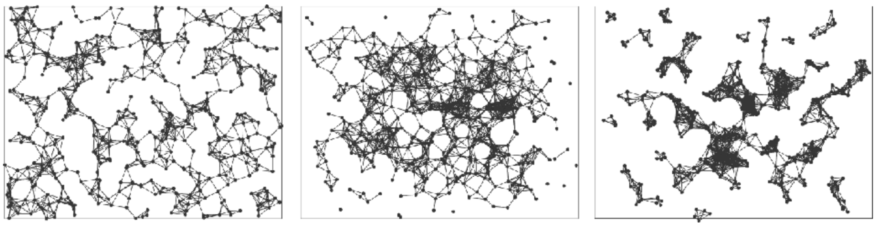

Figure 7.8. Geometric graphs corresponding to stationary node location distributions for random walk, random waypoint, and nomadic group mobility models. Differences, especially in terms of clustering, are clearly visible.

To summarize, the main short-term research problems we have seen are related to inclusion of geometric characteristics to network abstractions. This is a necessity for enabling effective network self-organization and optimization via topology control. Enabling reaction and optimization based on dynamic network characteristics also requires deep research work for developing abstractions to describe network dynamics. Further development of dynamic graph theory is certainly one of the major issues we see.

5. Hybrid Networks and 4G

Although there will be some commercial ad hoc systems that can be made successful as a standalone solutions, it is highly probable that different *hybrid network* approaches might be a real commercial route towards large-scale use of ad hoc networking principles. As the user mobility is increasing and many different local area applications become possible, there will be new opportunities to deploy limited local area ad hoc networks – these applications can include different games, community services, shopping-mall guides, etc. The need to provide very high bit-rates and cope with variety of network loads will also mean that the use of hybrid network architecture may become very attractive also for operators and manufactures.

The research community has increased its attention towards different hybrid wireless network architectures. The considered hybrid architectures are including full integration of MANETs with cellular and WLAN infrastructures, combination of multihop radio relying with cellular systems, and infrastructure support to provide high-capacity wireless networks on demand. There are different possibilities to classify hybrid architectures. Siva Ram Murthy & Manoj ([Murthy and Manoj, 2004]) divide hybrid architectures to (a) *Systems with Host-cum-Relay Stations* and (b) *Systems with Dedicated Relay* stations, which is a quite good basic differentiation. The former class has got somewhat more attention, but there has been also recent work in the latter domain.

Approximately the systems with dedicated relay stations are less flexible, and in certain sense are trying to use multihop and ad hoc principles to *enhance* existing network architectures. The systems with host-cum-relay stations offer more radical opportunities also in the field of business models, billing, and deployment. We are referring the interested reader to specific suggestions such as *multihop Cellular Network* (MCN) ([Lin and Hsu, 2000; Ananthapadmanabha et al., 2001]), iCAR (Integrated Cellular and ad hoc relaying system) by Wu et al. (in [Wu et al., 2001]), Hybrid Wireless Network Architecture (presented in [Hsieh and Sivakumar, 2001]), and highly interesting SOPRANO-architecture (Self-Organizing Packet Radio Networks with Overlay) proposed by Zadeh et al. ([Zadeh et al., 2002]). Other interesting proposals include, *e.g.*, MuPAC (Multi-power Architecture for Cellular Networks), TWiLL (Throughput Enhanced Wireless in Local Loop), A-GSM (Ad Hoc-GSM) and even 3GPP discussion on Opportunity Driven Multiple Access (ODMA) can be in part seen as a step towards hybrid architectures ([Aggelou and Tafazolli, 2001; 3GPP TSG RAN WG2, 1999; Manoj et al., 2004; Kumar et al., 2002]). Recently amount of submissions and discussion on hybrid and relay based systems has been increasing also in Wireless World Research Forum (WWRF) especially by the industry members showing that there might be momentum building up towards industrial development.

Mesh and Hybrid Deployments

Our own recent theoretical work has been focusing on understanding the opportunities and limitations of N-layer hybrid architectures. The N-layer architecture refers here to the possibility to build hierarchical architectures or overlays, where for example 802.16 network can be attached to provide broadband backbone support for 802.11 wireless hot spots. It seems that mesh networks as 1-layer or 2-layer architectures can be built quite efficiently based on ad hoc networking principles, but a lot of work is still required to understand business models, provide adequate billing mechanisms, optimize network performance (especially if multiradio approach is used).

Hybrid architecture deployments with different relying options require even more research and development work, but in our opinion they are very promising. They should not be seen as a threat by incumbent operators and manufacturers, in fact, the hybrid architectures open up many possibilities for better optimization and innovations on billing and applications domains. However, the pure spectral efficiency should not be over emphasized, especially if one is considering voice-communications (or limited video-streaming) and large-coverage areas. It is very difficult to build up commercially viable alternatives for the single-hop cellular networks. Hence, one has to be careful on the objectives of the hybrid ad hoc network approach, in our opinion they should not be “marketed” as research alternatives for cellular systems, but as systems that increase flexibility and business opportunities (and in the case of data communications can also increase a *local* spectral efficiency and network capacity).

Ad Hoc Boundaries and Applications

We expect that if the hybrid ad hoc network architectures become ubiquitous there will be clear application based boundaries for the network use. The localized applications, such as applications using Personal Area Networks (PANs) for gaming and file-sharing will be based to pure ad hoc networking, a number of application are based to hybrid architecture and can opportunistically use either ad hoc, or longer-range single-hop radio capability for communications, this application domains may well include for example vehicular applications. Even many local area applications will exhibit hybrid performance, as some parts of the system may require infrastructure support, *e.g.* due to need for billing or authentication.

6. Discussion and Conclusions

Although ad hoc networking has not become rapidly as ubiquitous as some of the proponents had been estimated, it seems that many principles that have been developed are finally finding their place towards real deployed systems. Many of the mobile ad hoc network principles are directly usable in the case of mesh networks and range extending wireless relying systems. Moreover, the sensor network applications and hybrid architectures might mean that ad hoc networks might become also a direct part of the future systems. One of the major advantages that commercial, hybrid architectures are exhibiting is the fact that cooperation between nodes can be measured and ensured much more efficiently than in the case of completely free ad hoc networks.

Complexity and Cognition

In this last section, we dare to speculate with the longer-term research focus. We have already seen that building efficient wireless ad hoc networks (hybrid or standalone) requires integration of several different techniques, and adaptivity. This leads fundamentally to issue that network must be *aware of the changes in its environment* and it must be capable of *adapting to changes in optimized and cooperative manner*. This means the systems will become rather complex. Over the last decade or so, the adaptivity boundary has been pushed from Physical Layer towards the whole system. In the case of relatively well defined systems, it is possible to use "classical" algorithmic adaptivity. However, if we need to have distributed decision making and support for optimization that takes in account many parameters and different, even mutually orthogonal, goals, it is quite possible that we need to consider the use of *machine learning* based methods. This is, in fact, the initial suggestion that Mitola was making, when he was introducing the concept of *cognitive radio* (see [Mitola, 2000]).

Mitola presented a model-based competence for software radios, and defined also an early prototype of RKRL (Radio Knowledge Presentation Language). We argue that this approach should be scaled further to include the use of cognitive decision making (optimization) also at the network layers ([Clark et al., 2003; Mähönen, 2004]). One of the work items emerging from our group has been the idea of Network Knowledge and Policy Representation Language - NKPRL). The main idea is that the high level goals and policies for ad hoc network should be presented in the machine readable form, and these representations could be then used by intelligent network elements on deciding what is the best interoperability and cooperation mode between nodes. In some sense, one could see NKPRL as a superset of the spectrum policy language XG in the networking domain.

An interesting question related to the NKPRL development is the choice of abstractions in network descriptions. As an example, graphs form perhaps the most fundamental network abstraction, used by practically all networking protocols suggested until today. Typically nodes that are handling the packets of the protocol under discussion are identified with vertices of the graph, and connections between these nodes are represented as edges. Naturally, depending on the layer of the protocol in question, each edge may consist of a number of actual, physical links. However, we believe there is a need also in network research for developing higher level abstractions for describing and, perhaps much more importantly, reasoning about large classes of networking phenomena.

Further, we would like to see the abstractions as groundwork for developing *network archetypes*, common abstractions with substantial reasoning power that could be applied into cognitive networks. Essentially, we see the network archetypes as a way cognitive network could describe its "self-image" in mathematically precise sense. Reasoning mechanisms could then be applied to decide on which actions to take if this self-image is unsatisfactory, that is, the network requires modifying. In fixed networks the observations of "small world", "scale-free" and "rich club" phenomena could be seen as first steps towards this, but inclusion of geometric relations and network dynamics inherent in ad hoc environments requires great deal of further research.

Conclusions

Wireless Multihop and Ad Hoc network paradigms have certainly many attractive features that can be used to enhance the future 4G network architectures. We have also argued that if the cognitive radio and network capabilities with the topology awareness is included to network architecture, then MANET -type of networking can become quite viable and efficient way to deploy wireless services. One of the challenges for ad hoc networking has been actually on getting enough *standardization* momentum behind the technology. Although, the basic paradigm of MANET is specifically to build ad hoc systems, we nevertheless need to agree on transmission and protocol issues. The only major effort in more formal standardization domain has been MANET working group of IETF (Internet Engineering Task Force). However, the charter of MANET is focused to routing issues, and even in the routing domain the work has progressed relatively slowly towards the consensus. The standardization efforts (*de facto* or *de jure*) definitely are needed to be increased, before ad hoc networking could become more commonplace as pointed out by Toh et al. ([Toh et al., 2005]).

The rapid expansion of IEEE 802.11 based ("WiFi") networks combined with a high potential of IEEE 802.16 ("WiMAX") is leading us to believe that at least low-mobility, mesh-type of ad hoc networks may become quite ubiquitous in the near future. We are arguing, based on experimental results done by ourselves and others, that if one is keeping the hop-count relatively low a quite good quality of service with low complexity of network can be provided. This kind of network architecture with low-mobility can provide an excellent platform for a lot of new data services, but can also provide a tempting alternative for VoIP service provision that include *wireless roaming* support without (costly) support for high mobility. Our scenario to use low-mobility ad hoc networks for data and VoIP services as a *low-cost networking model*, and perhaps some special applications (such as vehicular networks), may be a right economical incentive to make ad hoc networking reality. Hence, we conclude by pointing out that it is now time to start to also consider economical and business models for ad hoc networking.

Acknowledgments

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Notes

1. Spatial domain cooperation might be an important issue in the case of interference limited systems that are based, *e.g.* to spectrum agile cognitive radio technology or for topology controlled systems.
2. We shall speak of only frequency domain to simplify the discussion. Most of the techniques presented are as valid in other multiple access and channelization mechanisms, including TDMA and CDMA based networks. Nevertheless frequency domain cooperation seems to be at present most topical, as it is the method of choice for, for example, IEEE 802.11 based Ad-Hoc networks.
3. Geometric graphs (see [Penrose, 2003]) are graphs where vertices are located on a planar region for example, and edges connect vertices that are close enough in a given norm. Thus their structure can be expected to be similar to those of interference graphs of ad hoc networks.

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