Wireless Ad Hoc Networks: An Overview

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Abstract. This tutorial provides a general view on the research field of ad hoc networks. After a definition of the concept, the discussion concentrates on enabling technologies, including physical and medium access control layers, networking and transport issues. We find discussions on the adequacy of enabling technologies for wireless multihop communication, specifically in the case of the pervasive Bluetooth and IEEE 802.11. Then, a variety of dynamic routing protocols are presented and specific issues that are relevant in this context are highlighted. After a short discussion on TCP issues in this context, we look at power awareness, which is a very important issue in this scenario. Finally, we discuss proposals that aim at maintaining Service Level Agreements in isolated ad hoc networks and ad hoc networks connected to fixed networks.

Keywords: Ad hoc networks, multihop wireless networks, wireless networks, mesh networks.

1 Introduction

Wireless ad hoc networks are formed by devices that are able to communicate with each other using a wireless physical medium without having to resort to a pre-existing network infrastructure. These networks, also known as mobile ad hoc networks (MANETs), can form stand-alone groups of wireless terminals, but (some of) these terminals could also be connected to a cellular system or to a fixed network. A fundamental characteristic of ad hoc networks is that they are able to configure themselves on-the-fly without the intervention of a centralized administration.

Terminals in ad hoc networks can function not only as end systems (executing applications, sending information as source nodes and receiving data as destination nodes), but also as intermediate systems (forwarding packets from other nodes). Therefore, it is possible that two nodes communicate even when they are outside of each others transmission ranges because intermediate nodes can function as routers. This is why wireless ad hoc networks are also known as multi-hop wireless networks.

⋆ This work was partially supported by the Euro-NGI Network of Excellence of the European Commission and the Spanish CICYT Project TSI2007-66637-C02-01, which is partially funded by FEDER.

D. Kouvatsos (Ed.): Next Generation Internet, LNCS 5233, pp. 746–766, 2011.

Compared to cellular networks, ad hoc networks are more adaptable to changing traffic demands and physical conditions. Also, since the attenuation characteristics of wireless media are nonlinear, energy efficiency will be potentially superior and the increased spatial reuse will yield superior capacity and thus spectral efficiency. These characteristics make ad hoc networks attractive for pervasive communications, a concept that is tightly linked to heterogeneous networks and 4G architectures.

The need for self-configurability and flexibility at various levels (for example, dynamic routing or distributed medium access control) poses many new challenges in wireless ad hoc networks. Cross-layer optimization can significantly improve system performance and thus we will discuss some cross-layer issues here.

This tutorial concentrates on enabling technologies, including physical and medium access control layers, networking and transport. Research in middleware and security in this context is not considered.

Depending on their communication range, wireless ad hoc networks can be classified into Body (BAN), Personal (PAN) and Wireless Local (WLAN) Area Networks. A BAN is a set of wearable devices that have a communication range of about 2 m. The second type, PANs, refers to the communication between different BANs and between a BAN and its immediate surroundings (within approximately 10 m). WLANs have communication ranges of the order of hundreds of metres. The main existing technology for implementing BANs and PANs is Bluetooth, while for WLANs the main option is the family of standards IEEE 802.11. Although ad hoc networks are not restricted to these technologies, most of the current research assumes Bluetooth or IEEE 802.11 to be the underlying technologies.

After a general introduction, this tutorial discusses the main characteristics of Bluetooth, also considering open issues such as scatternet formation and real-time traffic support. The IEEE 802.11 technology is also considered: first we look at the basic functioning of the system in ad hoc mode and then we elaborate on its shortcomings for multi-hop communication, namely the lack of efficiency of the RTS/CTS mechanism and the impact of the difference between transmission and carrier sense ranges. Some proposed solutions are discussed briefly.

Routing is the most active research field in ad hoc networking. In this context, it is closely related with different communication layers. Minimizing the number of hops is no longer the objective of a routing algorithm, but rather the optimization of multiple parameters, such as packet error rate over the route, energy consumption, network survivability, routing overhead, route setup and repair speed, possibility of establishing parallel routes, etc. We compare different types of proposed routing algorithms and as a means of example we illustrate the functioning of a non-location based on-demand unicast routing protocol: DSR. Thereafter, we describe other algorithms of the same type (AODV), some proactive protocols (e.g. OLSR) and some location based schemes with their associated forwarding mechanisms (e.g. DREAM, LAR, Greedy Forwarding). During the discussion, we also point out specific issues that have to be considered in wireless ad hoc networks: for instance, two disjoint routes may have mutual influence if a node in one route is within the transmission range of a node in the other route, which has an impact on the construction of parallel routes.

The use of TCP over wireless links is known to present many problems. Communication over wireless multi-hop networks inherits these problems but also introduces some additional issues: the nodes mobility introduces unfairness between TCP flows, route failures lead to unnecessary congestion control and MAC contention reduces throughput in long routes. We also look at the proposed solutions briefly.

Since most wireless terminals can be expected to have limited energy storage, power awareness is very important. This subject spans across several communication layers. We pay attention to different power saving approaches. Objectives are not only the reduction of transmission power, but also the management of sleep states or the extension of network survivability through energy aware routing.

It may seem incoherent to deal with Quality of Service (QoS) support in such dynamic systems with unreliable wireless links. However, some authors have presented proposals to support QoS in isolated ad hoc networks, including QoS oriented MAC protocols suitable for distributed systems, QoS aware dynamic routing protocols, DiffServ in wireless multi-hop networks and resource reservation protocols such as INSIGNIA and SWAN. We study and compare these schemes and discuss new proposals for end-to-end QoS support in ad hoc networks attached to fixed networks through inter-network cooperation.

2 Enabling Technologies

In this section we find a discussion on some of the main enabling technologies for ad hoc networks, i.e. Bluetooth, IEEE 802.11 and Ultra-Wide Band radio.

2.1 Bluetooth

Bluetooth [33] is a single-chip, low-cost, radio-based wireless network technology suited for ad hoc networks, with communication ranges in the order of 10 m. The single-chip design makes this technology specially useful for small terminals with low energy storage capacity. It operates in the unlicensed industrial, scientific and medical (ISM) band at 2.40 to 2.48 GHz.

The physical channels are separated by fast Frequency Hopping Spread Spectrum (FHSS), using 79 carriers in most countries. Hopping slots have a duration of 625 us. In order to save power, this technology incorporates a powerful energy management architecture that comprises four different power consumption states.

Terminals arrange themselves in piconets, sets of terminals with one device functioning as master and up to other seven terminals functioning as slaves. In principle, any device can become a master or a slave. The master determines a hopping sequence and all the slaves use this hopping sequence to communicate with the master. Different piconets have different hopping sequences. Direct communication between slaves is not possible.

Terminals that are within the coverage areas of two or more masters may work as connections between different piconets. Such a terminal, called gateway, can belong to different piconets simultaneously on a time-division basis. A set of connected piconets forms a scatternet.

Links use Time-Division Duplex (TDD). The communication links are of two types depending on the arrangement of the time slots:

– Synchronous Connection-Oriented Link (SCO). The master reserves two consecutive time-slots for the forward and return directions respectively. Each SCO link supports 64 Kb/s on each direction with optional forward error correction (FEC) and no retransmission.
– Asynchronous Connectionless Link (ACL). The master uses a polling scheme, where one, three or five consecutive slots can be allocated to a link. FEC is optional. Data rates are up to 433.9 Kb/s per direction in symmetric links and up to 723.2 Kb/s / 57.6 Kb/s in asymmetric links. Headers are used to enable fast retransmission.

The scheduling of polling intervals for ACL links in view of service differentiation and provisioning of delay bounds is not specified in the system and is thus open for research (see, for example, [5]).

The topology of multihop networks largely depends on which terminals function as gateways between picocells. Scatternet formation is thus a relevant and difficult research issue because it affects topology significantly and has a large impact on the system performance. We can find a recent overview of scatternet formation and optimization protocols in [4].

Another research issue with a growing interest, in view of the future 4G vision of heterogeneous networking, is the coexistence between this technology and IEEE 802.11 (see e.g. [32]).

2.2 IEEE 802.11

The family of standards IEEE 802.11 [1] comprises the standards IEEE 802.11, IEEE 802.11b, IEEE 802.11g and IEEE 802.11a, amongst other standards that deal with specific issues such as security, service differentiation, etc. IEEE 802.11 provides wireless and infrared connectivity, but all implemented products use the unlicensed radio bands of 5 GHz (for IEEE 802.11a) and 2.4 GHz (for the rest).

The physical layer offers a number of channels. A set of terminals that use the same channel and are within the communication range of (some of) the other terminals of the set is called Basic Service Set (BSS). The number of physical channels depends on whether BSSs are multiplexed by using FHSS, Direct Sequence Spread Spectrum (DSSS) or Orthogonal Frequency Division Multiplexing (OFDM) techniques. Also, the communication rates per channel depend on the modulation, multiplexing, and forward error correction coding rates, ranging from 1 Mb/s to 54 Mb/s.

In the context of ad hoc networks, users belonging to the same BSS share the medium by means of a distributed random access mechanism called Distributed

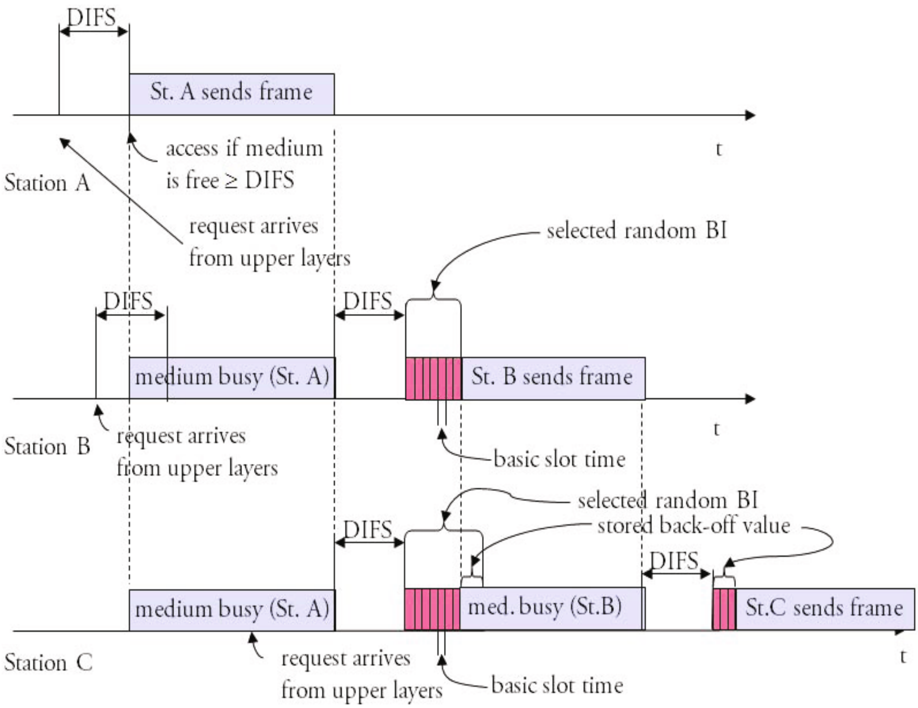

Fig. 1. Basic functioning of DCF

Coordination Function (DCF), basically a Carrier-Sense Medium Access with Collision Avoidance (CSMA/CA) technique.

Fig. 1 illustrates the basic functioning of DCF. There, we see how three stations behave as a function of time if they are all within reach of each other. When a Mobile Station (MS) gets a frame from upper layers to transmit, it first senses the channel to determine whether another MS is transmitting. If the MS has sensed the channel to be idle for a period of time equal to the DCF Inter Frame Space (DIFS), which is a quantity equal for all stations, then it starts transmitting the frame. Otherwise, as soon at it senses the channel to be busy, it will defer the transmission. When deferring, the station will continue sensing the channel.

At the point in time when the medium becomes idle again, the station will continue sensing and it will wait for the period DIFS to elapse again. If the medium becomes busy during this period, the station will go back to the deferring state again. However, if the medium remains idle for this DIFS period, the station will go to the back-off state.

When entering the back-off state, the MS selects a Back-off Interval (BI) randomly between zero and a Contention Window period (CW). The quantity CW is an integer number of basic time slots. If the medium remains idle for the duration of BI, then the station transmits the frame. However, if the medium

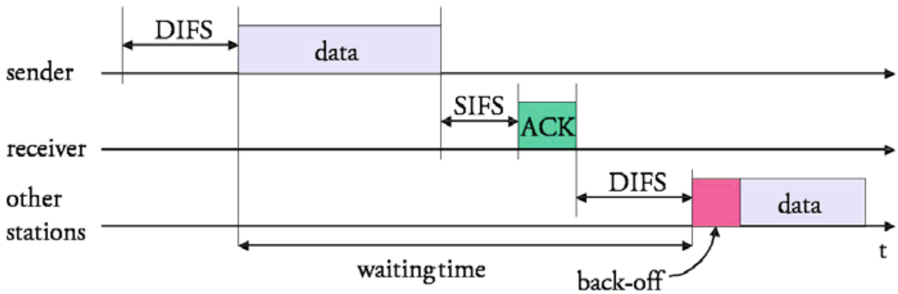

Fig. 2. Acknowledgements for DCF

becomes busy before the BI elapses, then the MS stores the remaining BI time (that is, the value of the chosen BI minus the elapsed time since entering the backoff state).

A collision will occur if two or more MSs select the same BI (provided the condition stated above, that the frames coexist spatially at one or more of the receiving stations). When a collision occurs, the stations that have caused the collision sense the medium again for DIFS and go again to the back-off state, selecting a new BI randomly with the value of CW doubled. The other stations, which stored their remaining BI times, also wait for DIFS and then go to the back-off state with BI equal to the stored value.

The value of CW is doubled every time that a station tries to transmit a given frame and a collision occurs, until a maximum CW (denoted CWmax) is reached. When this maximum value is reached, the BI will be randomly selected out of the interval [0, CWmax].

There is a maximum number of retransmission attempts: if the station has tried to transmit the frame this number of times and a collision has always occurred, then the station gives up trying to transmit the frame.

The radio transmission channel is relatively unreliable and the probability of transmitting a frame successfully is highly variable, even if there is no competition from other stations. Therefore, in IEEE 802.11 DCF, frames that have a single destination (which will be the case we will concentrate on) have a corresponding reception acknowledgement. This is illustrated on Fig. 2, where we show the behaviour of one transmitting station, the corresponding station (receiver) and a third station that has received a request to transmit from upper layers after the first station. After a station has transmitted the data frame, it will wait for an acknowledge frame (ACK) to arrive after a time period SIFS (Short IFS). The size of SIFS is unique for all stations and is smaller than DIFS. In this way, we guarantee that the first frame that is transmitted after the data frame is the acknowledgement of that frame and not any other data frame (unless the transmission medium fails temporarily).

An optional feature of DCF is the Request-To-Send and Clear-To-Send extension (RTS/CTS), which is common in commercial implementations. This option prevents many collisions induced by the *hidden-terminal problem* and the *exposed-terminal problem.* These problems are of major relevance in multihop wireless networks. The former problem consists in the following. Assume that Station A intends to send a frame to Station B. Station A will be able to hear only some but not necessarily all transmissions from other stations affecting Station B, thereby assuming that the medium is free when it is busy at its intended destination node. The exposed-terminal problem is complementary: Station A could refrain from sending data when hearing transmissions that do not arrive to Station B. To overcome these problems, the MS first transmits an RTS message and waits for a CTS message from the recipient before beginning data transmission. RTS and CTS frames also include the size of the data to be sent, so that a station hearing an RTS/CTS frame granting access to a different station refrains from sending an RTS to the medium for the duration of the indicated transmission time.

Synchronization and management of power saving modes are distributed but they suffer from scalability problems. This is because they are based on the periodical transmission of beacons that have to compete for medium access.

DCF provides best-effort service to higher layers, there is no differentiation between types of traffic. There have been many proposals for introducing service differentiation in DCF, some of them incorporated to the standard IEEE 802.11e [2].

DCF is known to be rather inefficient for wireless multihop communication. In particular, the RTS/CTS mechanism does not fully counteract the hidden-terminal problem because the power needed for interrupting a packet reception is much lower than that of delivering a packet successfully [3]. Some proposed solutions involve using busy tones, adjustable power or directional antennas, but this may not always be practical. For example, a recently proposed solution is to send the CTS only if the received power of the corresponding RTS is larger than a certain threshold [3], but this reduces the effective transmission range. For the design of new MAC mechanisms, more research is needed to analyze the effect of the presence of multiple stations within the transmission, reception or interference ranges of a given station.

2.3 Ultra-Wide Band Radio

The development of Ultra-Wide Band radio (UWB) is progressing quickly. The idea behind UWB, a technology that has also received the names of *baseband, carrier-free* or *impulse* radio, is to use electromagnetic signals with a very wide spectrum (with -10dB bandwidth in excess of 25% of the central frequency, typically in the order of several GHz) so that the power spectral density is so low that the system can coexist with existing licensed spectral bands. Typically, low power, low range communications are a natural context for UWB. This is especially true in environments where multipath propagation is important, such as indoor channels. This technology also has the property of supplying accurate ranging information between UWB devices, which can be used to improve communication at higher layers (e.g. routing). UWB technology has many options in IEEE 802.15.3 group's work towards low-power BANs with 10 m communications range and data rates above 100 Mbit/s, and on IEEE 802.11.4 group's activities aimed at low data rate support with ranging functionality.

The Federal Communications Commission (FCC) of the U.S.A. allowed for commercial operation of products using UWB-RT with at most -41.3 dBm/MHz between 3.1 and 10.6 GHz, differentiating between indoor and outdoor operation in neighbouring bands. The European Telecommunications Standards Institute (ETSI) is also regulating an identical power level between the mentioned frequency values, but with more restrictive values in neighbouring bands.

Several projects have investigated aspects of UWB with the support of the European Commission, such as Ultra-wideband Concepts for Ad hoc Networks (UCAN), Ultra Wideband Audio Video Entertainment System (ULTRAWAVES) or Pervasive Ultra-wideband Low Spectral Energy Radio Systems (PULSERS), with the participation of some companies such as Philips, Acorde, Telefónica, VTT or IMST. In the U.S.A., several companies have been developing UWB radio chips, including Freescale, Time-Domain, Alereon, Multispectral Solutions, Intel and Texas Instruments. Major Japanese companies, such as Matsushita, Sony, Sharp, JVC, Pioneer, NEC and Mitsubishi, considered UWB as an ultra-fast wireless interface.

Given the fact that UWB systems are supposed not to interfere with other communication systems, we can expect that UWB will be complementing systems such as IEEE 802.11 in future. IEEE 802.11 systems have larger communication ranges but lack precise ranging features; also, the impact of obstacles and multipath propagation is different in both physical layers. Therefore, the symbiosis between both systems could significantly boost the performance perceived by the user of wireless multihop networks.

3 Routing Issues

Routing protocols for wireless multihop networks are dynamic due to the potential node and link mobility.

Unicast routing protocols can be classified in the following way:

- Proactive vs. reactive. Proactive protocols periodically maintain the routing information so that any node can use a existing route to reach a destination at any time. This is the rule in fixed networks, but in mobile ad hoc networks this would require a very frequent update of routing information for all nodes, which implies a lot of overhead. Reactive protocols, on the contrary, obtain the necessary routing information only when a route is needed between two nodes; the route is maintained only when the route is active. This is why reactive protocols are also called *on-demand* protocols. Reactive protocols imply lower overhead than proactive ones, but they suffer from route setup delays when a communication flow is to start. There also exist hybrid protocols, which combine proactive mechanisms within a local scope and reactive mechanisms within global scope (e.g. the Zone Routing Protocol [19]).
- Location-based vs. non location-based. Location-based are protocols where some means exist by which nodes can obtain some knowledge about their

relative physical (or geographic) position with respect to other nodes, such as distance or angle. Non location-based protocols do not rely on this information: nodes only know which links are active. Similarly to routing protocols in fixed networks, non location-based protocols spread topology information about which pairs of nodes are immediate (one hop) neighbours. In contrast to this, networks using location-based protocols can make use of the geographical information to significantly improve the efficiency of the route setup process in terms of speed and overhead, as we will see. In practice, the major drawback of location-based protocols is that nodes are required to incorporate a system that provides information about their physical position, such as the Global Positioning System (GPS). We find a good overview of location based protocols in [20].

– Hierarchical and flat. Especially in large ad hoc networks, arranging nodes in clusters for routing purposes can increase the efficiency of the routing protocol. Also, introducing hierarchies of routing protocols can be applied to distinguish routes pertaining to the ad hoc network only from routes linking the ad hoc networks with a gateway to a fixed network. Clustering has a long research history starting from the times of packet radio, but it is still an active research field: the formation of clusters can be made according to many different criteria, such as nodes' mobility patterns, traffic patterns, nodes' capabilities (e.g. energy storage, processing power, etc.). An example of a hierarchical on-demand routing protocol is the Cluster-Based Routing Protocol (CBRP) [15].

To illustrate the functioning of dynamic routing protocols, we consider the Dynamic Source Routing (DSR) protocol [6], [7]. DSR is, together with the Ad Hoc Distance Vector protocol (AODV) [8], the most widely studied routing protocol for mobile ad hoc networks. DSR does not require location information and it is relatively simple because it is a flat, on-demand protocol. We consider networks where all nodes have identical capabilities and responsibilities.

In DSR, when a source needs a route to a destination, it initiates a route discovery process to locate the destination node. The source node floods a Route Request packet (RREQ) requesting a route for the destination. A Route Reply (RREP) packet is sent back to the source either by the destination node or by any node that knows how to reach the destination. The addresses of intermediate nodes are accumulated on the RREQ and RREP packets. Every node in the network uses the information in the RREQ and RREP packets to learn about routes to other nodes in the network. This information is stored in route caches.

Once a source node receives an RREP, it knows the entire route to the destination. If a link contained in the route breaks during the transmission of data packets, the transmitting-side node uses a different path if it has an alternate route cached; otherwise, it reports an error back to the source and leaves it to the source to establish a new route.

The already mentioned AODV protocol is similar to DSR, but it is table based rather than source based. AODV is restricted to networks of symmetric links because the RREP packets are sent via the reverse route. However, a one-hop RREP acknowledgement packet can be used to counteract this problem [9], [10]. Expiry timers are used to keep the route entries fresh.

DSR and AODV maintain the needed routes dynamically, have a relatively low overhead and avoid the formation of routing loops. A drawback is their relatively low scalability with the number of nodes. DSR and AODV are not shortest path algorithms in the sense of least number of hops: since nodes reply to the first arriving RREQ, these protocols select the route to the destination that is fastest at the moment that the route is set up.

DSR and AODV require a relatively low processing power, since they do not resort to cost functions for optimal route search. This relieves the nodes from calculating such a function every time a routing packet is forwarded. However, this is an obstacle for using multiple parameters for route optimization. In practice, in ad hoc networks we could be interested in routing for maximum route stability, minimum energy consumption, minimum number of hops, maximum link reliability, QoS support, etc.

Many improvements have been proposed for DSR and AODV [9]. For example, a route can be repaired faster if the node at the transmitting side of the broken link starts a route discovery process by itself. In this case of repairing routes, Query Localization limits flooding to nodes close to the original route. Also, control overhead can be reduced by limiting the area that is flooded during a route discovery process (Expanding Ring Search). The size of this area can be calculated by using information gathered from previous source-destination data flows, a central idea of the Relative Distance Micro-Diversity Ad Hoc Routing protocol (RDMAR) [11]. In RDMAR there is no need for location information systems: the source-destination distance is estimated from the number of hops used in the previous data flow, the time elapsed since the previous data flow finished, the velocity of the source and the destination nodes and the transmission range.

Flooding for route setup can cause many collisions, which is known as the *Broadcast Storm Problem.* Many heuristics have been proposed to counteract this problem, such as staggering the route search packets at intermediate nodes or re-broadcasting with probability $p<1$ (see, e.g. [28]).

Many other non location-based, flat, reactive routing protocols exist. The Associativity-Based Routing protocol (ABR) [12] and the Signal Stability Adaptive (SSA) [13] protocol are source-initiated protocols that tend to select the routes with the most stable links. Although routes are built on demand, a periodic beaconing mechanism is needed for establishing the stability of the links. Protocols based on ant colony algorithms have been proposed, but they have poor scalability properties with the number of nodes and data flows.

Some other algorithms do not rely on flooding control messages. The Temporary Ordered Routing Algorithm (TORA) is based on the construction of a directed acyclic graph (DAG) for each destination [14]. In this way, topology changes induce a very limited amount of control messages. TORA is specially indicated for highly mobile networks.

Most proactive, flat, non location-based routing protocols are derived from existing routing protocols for fixed networks. This is the case of the Destination-Sequenced Distance Vector (DSDV) protocol [16], which uses a distance vector shortest-path (in terms of hops) algorithm where incremental changes are exchanged more frequently than full routing information. Another protocol of this kind is the Optimized Link State Routing (OLSR) protocol [17], a link state protocol where the amount of control messages is reduced by restricting the rebroadcast of control messages to a subset of nodes (the *Multipoint Relays*). OLSR is possibly the most scalable proactive, flat, non-location based protocol [18].

Location based protocols can have the location information stored in some of the networks nodes or in all of them. Also, the stored information can comprise the location of all the nodes or only of a subset. Depending on which option is taken, a location service is denominated *some-for-all, all-for-all, all-for-some* or *some-for-some.*

The Distance Routing Effect Algorithm for Mobility (DREAM) [21] is an all-for-all location service where all the nodes spread its location information periodically. The frequency and range of the information dissemination depends on the mobility of a node and the relative distance to the receivers of the information ('distance effect'); DREAM also includes forwarding. The Grid Location Service (GLS) is a some-for-all scheme where location information is stored according to a hierarchical cartesian grid. Other some-for-all location services are based in the concept of *quorum:* the network is divided subsets of nodes with non-empty intersections. The route setup process can be made with Greedy Packet Forwarding (GPF), which has several variations [20]. DREAM forwards route discovery packets by flooding within a zone defined by the transmitting node's position and the expected destinations area. Location Aided Routing (LAR) [22] is a forwarding strategy with two versions: the first is similar to DREAM, where flooding is restricted to an area that depends on the nodes' relative distances and velocities; the second allows route discovery packets to be forwarded only if the receiving node is closer to the destination node than the transmitting node. We can mention two hierarchical location based forwarding strategies: Terminodes [23] routing and Grid [24] routing. Terminodes combines proactive distance vector routing for local scope and reactive GPF.

Some protocols exist that are based on the construction of clusters. Usually, a cluster has a leader node. Different protocols differ in the way that clusters are built, how the cluster is chosen and the responsibilities assigned to the leader node. The Core-Extraction Distributed Ad Hoc Routing (CEDAR) [25] is a hierarchical routing protocol where a subset of nodes, called the core, is selected such that all nodes are at most one hop from the nodes of this subset. Core nodes execute a link state protocol where each core node knows the state of local links and stable, high-bandwidth links far away. A route is found on-demand by the core nodes, but this does not mean that the route itself has to traverse core nodes.

In unicast routing, it can be interesting to have multiple routes between two nodes. Reasons for this can be to speed up the route repair process, to increase the reliability of data delivery by sending duplicates of data packets along different routes or to distribute traffic according to QoS requirements. There are diverse proposals for multipath routing. For example, AOMDV [26] is a modified AODV protocol for multipath routing that seeks link-disjoint routes to the destination, that is, routes that have no common links but may share common intermediate nodes. Basically, RREQ packets include a field that indicates the first node traversed after the source node (that is, the immediate neighbour of the source they have passed). Upon reception of an RREQ, a node only re-broadcasts the packet if the mentioned field indicates a different first-hop node than other RREQ packets that have already arrived. AOMDV yields better end-to-end and lower routing overhead, especially with high traffic loads.

The role of wireless ad hoc networks as access networks is gaining interest. A relevant research issue therein is routing when the source or destination is a gateway to a fixed network. We can find relatively new contributions within this area, such as Load Balancing AODV (LB-AODV) [27], where nodes are arranged into groups in order to reduce the routing overhead. Nodes belonging to different groups may not forward packets originated in nodes of other groups. Another multipath routing protocol is Gossip [28].

Multicast routing protocols for wireless ad hoc networks can be classified into tree-based and mesh-based in general. Mesh based schemes are more robust because they yield multiple redundant routes, but resources are wasted as a result of unnecessary forwarding of duplicate data. In tree based schemes resource usage is optimized, but network mobility induces major reconstruction overhead and latency.

An example of a tree-based multicast protocol is MAODV [9]. In MAODV, a node joins a multicast group through RREQ packet flooding. When an RREQ packet arrives at a member of the multicast tree, it responds with an RREP. Since more than one node of the multicast tree may be reached by the RREQ, the source sends a Multicast Activation (MACT) packet along the selected route so that the involved nodes know that they have become part of the multicast tree.

A widely studied mesh-based multicast protocol is the On-Demand Multicast Routing Protocol (ODMRP) [29]. A node wishing to send multicast packets floods a Join Data packet throughout the network periodically. On receiving a Join Data packet, each multicast group member broadcasts a Join Table packet to all its neighbours. Multiple routes from a sender to a multicast receiver may exist due to the mesh structure created by the forwarding group members. There is no explicit join or leave procedure.

4 Transport Issues

The issues associated with the use of TCP on wireless channels have been widely studied. Random errors may cause Fast Retransmit, which implies halving the congestion window size. When errors are not frequent this is not necessary and it reduces the throughput. Errors may even cause transmission timeouts and thus a severe reduction of the congestion window. But in ad hoc networks, TCP is affected not only by wireless transmission errors, but also medium access contention in neighbouring hops and route failures due to mobility.

In general, the throughput of a flow is reduced when we increase the number of hops on one route from 1 to 3, due to contention at MAC level. Beyond 3 hops there should be no further throughput degradation, but in TCP flows there is a reduction in throughput beyond 3 hops due to contention between TCP data and acknowledgements. A measure to counteract this is to reduce the number of transmitted acknowledgements.

Experiments have also shown that increasing the mobility also has a negative impact on the throughput of TCP flows. Mobility induces route failures. While the route is repaired, packets and acknowledgements are en route are lost. At a given moment, no more packets are transmitted. If the TCP sender has not timed out before the route has been repaired, the first retransmission will not occur until the time out. If the route repair process is slower, it can happen that the TCP sender times out before there is a route available and thus the timer will be doubled. In conclusion, large route repair delays have a severe impact on TCP performance.

An idea for improving the performance of TCP is to use network feedback. This consists in letting TCP know that there has been a route failure and informing TCP that a route has been repaired [30]. The use of route caching in on-demand routing protocols may have a negative impact on TCP performance: although caching reduces route repair times, it may cause a flow to use stale routes [30].

Another issue that arises when a route is broken is how to choose the TCP window size and retransmission timeout value after a route has been repaired.

5 Energy Awareness

We should realize that issues such as QoS support, TCP performance, speed of routing repair processes, etc. are secondary if nodes have a high probability of running out of energy resources. As mentioned above, energy awareness in wireless ad hoc networks spans across several communication layers.

Battery technology has advanced very slowly if we compare it with the results achieved in integrated circuit technology and it certainly cannot be compared to the rate of growth in communication speeds. Therefore, saving transmission power will represent one of the most significant factors in the performance of wireless systems in the long term.

Several proposals in literature relate routing to energy awareness. In [35] we find two routing protocols designed for scenarios where the nodes can adjust their transmission power dynamically according to the effect of link layer error rates and consequent packet retransmissions. Such considerations motivate a routing protocol [36] based on a cost function that comprises the link error rate and the energy required for a single transmission attempt across the link.

The work in [37] and [38] compares routing schemes that aim at minimizing the transmission power when selecting a route to routing schemes that try to maximize the lifetime of the nodes in the network as a whole.

In [39] it is proposed to introduce the battery characteristics directly into a routing protocol using the remaining battery capacity as metric of the lifetime of each host.

The two objectives of minimizing the total transmission energy for a route and for all the network can lead to contradiction, for example in the case that several minimum energy routes have a common host, then the battery power of this host will be exhausted quickly. In [37] and [38] a new routing scheme is presented that aims at satisfying the two constraints simultaneously: the Minimum Battery Cost Routing algorithm (MBCR). This protocol aims at finding a route with the maximum total remaining capacity. Let us define $f_i(c_i^t)$ as a battery cost function of host n_i, where c_i^t represents the battery capacity of the host at time t. We can choose the cost function to be for example

$$f_i(c_i^t) = 1/c_i^t \tag{1}$$

The battery cost R_J for a selected route J will be then:

$$R_J = \sum_{i=0}^{D_J-1} f_i(c_i^t), \tag{2}$$

where D_J is the number of nodes belonging to the route J. To select a route with the maximum total remaining capacity, one should choose the route m that has the minimum battery cost:

$$R_m = min\{R_J \mid J \in A\}, \tag{3}$$

where A is the set containing all possible routes.

The Simple Energy Aware Dynamic Source Routing (SEADSR) [40] is a protocol that improves the network survivability while maintaining the simplicity of DSR. The basic idea behind this algorithm is as follows. When an intermediate node in an ad hoc network decides to forward a RREQ message (in the DSR fashion) that it has received, it introduces an additional delay τ before re-transmitting this message:

$$\tau = (C_{max} - C)\tau_{max}/C_{max}, \tag{4}$$

where C_{max} is the battery capacity, C is the current battery level and τ_{max} is a design parameter that represents the maximum delay introduced. We can appreciate that τ takes a value between 0 and τ_{max} and is directly proportional to the energy consumed by the node. As in DSR, the route selection will depend on the previously mentioned factors, but this additional delay establishes interdependency between the route selection and the battery levels of the nodes. The parameter τ_{max} plays an important role in the route selection. The larger the parameter τ_{max}, the larger the influence of the battery level will be against the other factors.

The use of directional antennas has the potential of reducing transmission power and also may increase the communication capacity of the network due to the higher spatial reuse. However, it introduces many new challenges for MAC and routing protocols. Research on directional antennas for ad hoc networking is relatively incipient. A good overview can be found in [31].

Besides reducing transmission power, there is also research in the direction of reducing energy consumption for reception. This is already incorporated to Bluetooth and IEEE 802.11 technologies, as well as contemplated in other alternative technologies such as ETSIs HIPERLAN family of standards. The most widely used strategies are schemes that allow terminals to switch off their transceivers temporarily. The power saving scheme in IEEE 802.11 is one of this kind, but it scales very poorly in ad hoc mode. A recent proposal is the Power-Aware Multi-Access protocol (PAMAS) [34]. This protocol conserves battery power by powering off a node when a neighbour is transmitting packets to another node. PAMAS uses a separate control channel for a node to probe whether the data channel is busy.

Energy consumption can be also reduced by adjusting the transmission power so that only just the necessary power to reach the receiver is employed. In IEEE 802.11, however, it is not straightforward to have nodes transmitting with different power because it would produce many collisions. A simple proposal is the Power Controlled Multiple Access (PCMA) protocol [41]. In this protocol, nodes use a busy tone to let their neighbours know what level of interference they can tolerate. If a node R can tolerate an interference level N, it will transmit a busy tone with power C/N, where C is a constant. This tone will be received at a neighbouring node X with power $g \cdot C/N$, where g is the gain of the link R-X. Node X will be allowed to transmit with a power not larger than $C/(g \cdot C/N)$. This implies that the power received at node R from node X will be smaller than N, assuming that the link is symmetrical in terms of gain. Despite the drawback of requiring the transmission of busy tones, PCMA improves aggregate throughput and reduces power consumption.

6 QoS Support

Providing QoS is a challenging area of future research in wireless ad hoc networks. The networks ability to provide QoS depends on the characteristics of all the network components, from transmission links to the MAC and network layers. In these networks, links have a relatively low, highly variable capacity and high loss rates. Besides, mobility provokes frequent link breakages. Finally, link layers typically use unlicensed spectral bands, making it more diffcult to provide strong QoS guarantees. If the nodes are highly mobile, even statistical QoS guarantees may be impossible to attain, due to the lack of suffciently accurate knowledge of the network states. Furthermore, since the available network resources (e.g., MAC congestion levels or battery state) varies with time, present QoS architectures for wired networks are unsuitable.

Important QoS components include: QoS aware medium access control, QoS oriented routing and resource-reservation signalling. QoS aware MAC protocols solve the problems of medium contention, support reliable unicast communications and provide resource reservation for real-time traffic in a distributed wireless environment. Among numerous MAC protocols and improvements that have been proposed, a protocol that can provide QoS guarantees to real time traffic in a distributed wireless environment is Black-Burst (BB) [43]. This protocol is built upon IEEE 802.11 DCF and has good QoS characteristics as far as the traffic flows have constant bit rates. An overview of proposed modifications to IEEE 802.11 for QoS support at MAC level, specifically providing traffic differentiation, can be found in [2].

QoS routing refers to the discovery and maintenance of routes that can satisfy QoS objectives under given resource constraints, while QoS signalling is responsible for flow admission control as well as resource reservation along the established route. INSIGNIA is the first QoS signalling protocol specifically designed for resource reservation in ad hoc environments [44]. It supports in-band signalling by adding a new option field in the IP header to carry the signalling control information. Like RSVP, the service granularity supported by INSIGNIA is per-flow. If the required resource is unavailable, the flow will be degraded to best-effort service. QoS reports are sent to the source node periodically to report network topology changes, as well as QoS statistics (loss rate, delay and throughput).

SWAN is an alternative to INSIGNIA with improved scalability properties. SWAN is a stateless network scheme specifically designed for wireless ad hoc networks employing a best-effort distributed wireless MAC [45]. Intermediate nodes do not keep any per-flow information and thus avoid complex signalling and state control mechanisms and make the system more simple and scalable. It distinguishes between two traffic classes: real-time UDP traffic and best-effort UDP and TCP traffic. A classifier differentiates between real-time and best-effort traffic. Then, a leaky-bucket traffic shaper handles best-effort packets at a previously calculated rate, applying an AIMD (Additive Increase Multiplicative Decrease) rate control algorithm. Every node measures the per-hop MAC delays locally and this information is used as feedback to the rate controller. Every T seconds, each device increases its transmission rate gradually (additive increase with increment rate of c bit/s) until the packet delays at the MAC layer become excessive. As soon as the rate controller detects excessive delays, it reduces the rate of the shaper with a decrement rate (multiplicative decrease of $r\%$).

Rate control restricts the bandwidth for best-effort traffic so that real-time applications can use the required bandwidth. On the other hand, the bandwidth not used by real-time applications can be efficiently used by best-effort traffic. The total best-effort and real-time traffic transported over a local shared channel is limited below a certain 'threshold rate' to avoid excessive delays.

SWAN also uses sender-based admission control for real-time UDP traffic. The rate measurements from aggregated real-time traffic at each node are employed as feedback. This mechanism sends an end-to-end request/response probe to estimate the local bandwidth availability and then determine whether a new real-time session should be admitted or not. The source node is responsible for sending a probing request packet toward the destination node. This request is a UDP packet containing a "bottleneck bandwidth" field. All intermediate nodes between the source and destination must process this packet, check their bandwidth availability and update the bottleneck bandwidth field in the case that their own bandwidth is less than the current value in the field. The available bandwidth can be calculated as the difference between an admission threshold and the current rate of real-time traffic. The admission threshold is set below the maximum available resources to enable that real-time and best-effort traffic are able to share the channel efficiently. Finally, the destination node receives the packet and returns a probing response packet with a copy of the bottleneck bandwidth found along the path back to the source. When the source receives the probing response it compares the end-to-end bandwidth availability and the bandwidth requirement and decides whether to start a real-time flow accordingly. If the flow is admitted, the real-time packets are marked as RT (Real-Time packets) and they bypass the shaper mechanism at the intermediate nodes and are thus not regulated.

The traffic load conditions and network topology change dynamically so that real-time sessions might not be able to maintain the bandwidth and delay bound requirements and they must be rejected or readmitted. For this reason it is said that SWAN offers soft QoS. The Explicit Congestion Notification mechanism (ECN) regulates real-time sessions as follows. When a mobile node detects congestion or overload conditions, it starts marking the ECN bits in the IP header of the real-time packets. The destination monitors the packets with the marked ECN bits and informs the source sending a regulate message. Then the source node tries to re-establish the real-time session with its bandwidth needs accordingly.

QoS routing is in charge of setting up the route for successful resource reservation by QoS signaling. This is a difficult task because optimal QoS routing requires frequent updates on link state information such as delay, bandwidth, cost, loss rate or error rate. This can result in a large amount of control overhead, which can be prohibitive for bandwidth constrained ad hoc environments. In addition, the dynamic nature of wireless ad hoc networks makes the maintenance of the precise link state information extremely difficult. Even after resource reservation, the QoS levels still cannot be guaranteed due to the frequent link failures and topology changes. Several QoS routing algorithms were published recently with a variety of QoS requirements and resource constraints [46].

There has been little research on the support of QoS when a wireless ad hoc network is attached to a fixed IP network. In this context, co-operation between the ad hoc network and the fixed network can facilitate the end-to-end QoS support. In [47], a new protocol is proposed that is based on the co-operation between a resource reservation protocol within the ad hoc network and a DiffServ domain in the fixed network. The resource reservation protocol is similar to SWAN, but it uses adaptive parameters according to feedback signals sent from the closest edge router in the DiffServ domain. In this way, the end-to-end delay of variable bit-rate, real-time traffic can be controlled efficiently.

Access networks in the Internet of the future can be expected to be heterogeneous. These networks will comprise a multiplicity of wireless and optical technologies, for example Passive Optical Networks (PONs), IEEE 802.11 or IEEE 802.16 [49]. Ad hoc network functionality can be also considered as a part of these heterogeneous access networks. In fact, some of the wireless nodes can be static and form what is called *mesh networks,* which will have higher efficiency thanks to the increased network stability.

A good overview on QoS support in wireless ad hoc networks can be found in [48].

7 Cross-Layer Issues

An example of the benefits we can obtain from a cross-layer approach is the work in [42]. The idea behind this recently developed protocol is that using power control such as in the PCMA medium access scheme [41] (discussed above) has an obvious impact on routing. This protocol contains a series of mechanisms in order to perform efficient power control and, at the same time, use an appropriate transmission power for establishing the route (i.e. the power used for transmission of RREQ packets in DSR or AODV).

Another example of the implications that protocol design has on other layers is the way that route maintenance is done in reactive unicast flat routing protocols (such as DSR or AODV) and whether the traffic is carried with UDP or TCP [9]. For UDP flows, re-constructing the route from the source may result in excessive packet loss and a route repair strategy closer to the broken link would be more effective in this case.

Due to the broadcast nature of radio, if omnidirectional antennas are used, two disjoint routes may have mutual influence if a node in one route is within the transmission range of a node in the other route. This has an impact on the construction of parallel routes with the purpose of distributing traffic load evenly or according to QoS requirements. Also, in the DS-SWAN scheme [47], this fact has to be considered when selecting the nodes that have to adapt their traffic shaping parameters.

In the ABR routing protocol [12], the periodic exchange of packets for determining the degree of associativity between nodes may constitute an obstacle for scheduling sleep modes in the terminals, thereby increasing power consumption.

Obviously, the interaction between TCP and the link layer is a very significant cross-layer issue and several proposals have appeared. Also, the effect of transmission power control on TCP is non-negligible, since the former yields routes with a larger number of hops and the latter behaves better with shorter routes in general.

8 Conclusions

This tutorial aims at giving some light on basic concepts and research challenges in wireless ad hoc networking. There are many aspects to point out in this relatively new research field.

Research in wireless ad hoc networks is receiving growing interest. This is a multidisciplinary subject, where the interaction between protocols at different layers is of paramount importance. In many cases, legacy protocols from fixed networks are not adequate for this type of networks and in most cases, new protocols are needed. Despite the relatively large amount of contributions in some areas, such as routing, many new challenges continue appearing.

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