# Wireless Adhoc Networks in the Metropolitan/Wide Area: Concepts and First Results

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*Abstract:* – This paper is dedicated to on-going research activities in the field of wireless metropolitan and wide area networks with Quality-of-Service (QoS) guarantees. We focus on self-organizing systems, so-called adhoc networks, which can operate without any wired infrastructure (e.g. cellular base stations) – except for some interface points providing interconnectivity to other networks like the Public Switched Telephone Network (PSTN) or the Internet. Obviously, the lack of a wired back-bone network implicates that routing, signalling and other management functions must be handled completely over the air in a self-organizing manner.

*Key-Words:* – Adhoc Networking, Radio Resource Management, Synchronization, IEEE 802.11

## 1 Introduction

Current 2$^{nd}$ and 3$^{rd}$ generation cellular wireless networks, like GSM and UMTS, rely on a wired infrastructure – a back-bone network that interconnects the base stations, which provide services to mobile users. Deployment of such a network is associated with high initial investments and its operation requires costly maintenance: Spectrum has to be licensed, base stations need to be build up on leased ground, the network must be permanently monitored and actively managed by its operator etc.

Meanwhile, some new concepts have evolved claiming to address many of the shortcomings mentioned earlier: So-called adhoc, multihop or mesh networks. The basic idea is that one end user's equipment is empowered to communicate directly with another one's (peer-to-peer communication) – without the need of any intermediate network node, like a cellular base station. A concept, which stems from packet radio networks developed in the 1970's in the context of battlefield and disaster recovery communication requirements [1]. Actually, the cellular concept is completely discarded and a mesh network is established instead. When a desired station is not within the immediate transmission range of a station, intermediate nodes are asked to forward the information. In other words, the data hops from node to node until it reaches its destination. There are some design choices to make regarding the network's architecture (flat vs. hierarchical), routing protocol (proactive vs. reactive vs. hybrid approaches), medium access control (sensing-based vs. dialog-based vs. scheduled), etc. [2] [3] [4].

A sample topology is given in figure 1, showing a network and a possible connection between two nodes, using a number of intermediate nodes for forwarding purposes. Please notice, that bidirectional connections, as shown in the example, are not a requirement for the solutions presented in this paper.

## 2 Challenging Aspects

### 2.1 Radio Resource Management

Today, most real-world implementations of an adhoc network use a single shared channel for their transmissions. The problem with this approach are collisions, which occur if two stations in the same geographic region transmit at the same time. A receiver exposed to both transmissions is unable to receive either of them because of extremely high co-channel interference. Therefore some kind of medium access control (MAC) is required. In addition to very simple schemes like ALOHA, there exist more sophisticated ones like the IEEE 802.11 carrier sense multiple access with collision avoidance (CSMA/CA) [5].

However, these multiple access schemes have one major drawback when it comes to QoS support: For in-

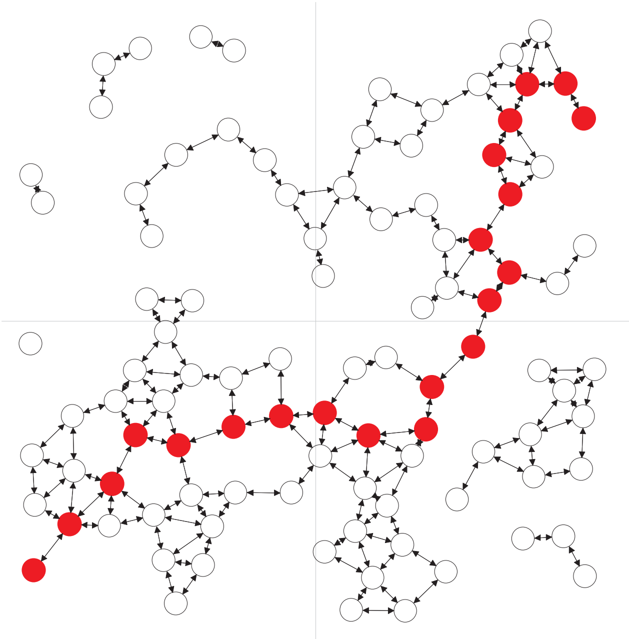

Fig. 1. Sample topology with 100 nodes

stance, the 802.11 Distributed Coordination Function (DCF) cannot provide guarantees whether and when a packet scheduled for transmission is actually put ”on-the-air”. As an example, consider the case when the MSDU transmission lifetime counter expires before the station is granted access to the wireless medium: Then the MSDU is simply dropped at the transmitter. Furthermore, the time required to gain access to the medium is non-deterministic, because of the unknown and unpredictable channel state and the back-off strategy, which creates pseudo-random delays.

While this situation is acceptable for best-effort packet-switching environments with few (if any) hops, such delay jitter and unpredictable behavior are not tolerable if multiple input streams are to be combined in a switching node and rescheduled for transmission. Therefore, a number of circuit-switched links is required. Once established, such a dedicated link is exclusively reserved for transmissions between two neighboring stations, that is, no other station shall be allowed to transmit on the same physical channel. A transceiver, which is capable of receiving multiple input streams simultaneously and which is also able to transmit more than one stream at a time, would be able to forward incoming streams with a minimal delay (one symbol). Thus, such an approach would allow many intermediate hops to occur, before a critical delay (say 150ms) is reached. Not to exceed this delay is crucial for interactive audio/video applications.

Obviously, several input/output streams demand different physical channels to be used for each transmission. Generally, this can be achieved by time division, frequency division, code division, and spatial division – or any combination thereof. Since there is no cellular structure any more, resource reuse can no more be achieved with fixed channel assignment (FCA) strategies – instead dynamic channel assignment (DCA) is required and, even more challenging, the DCA scheme must run in a completely distributed fashion over all network nodes, since no centralized management is desired.

Another tightly related issue is the transmitter power control. Of course it is useful for extending the mobile equipment’s battery life, but even more important, it is also an essential requirement for any reasonable code division multiple access (CDMA) system in order to reduce multiple access interference (MAI). Power management may also be used for optimization of the network topology [6]. A lot of relevant research on the field of transmission scheduling and channel assignment has already been done in the context of multihop wireless networks [7] [8].

### 2.1.1 Random Access Channel

The random access channel (RACH) is a shared, unsynchronized channel that provides an unacknowledged connection-less service to the network layer and is best suited for the exchange of short datagrams and other best-effort traffic. A node wishing to transmit some information to another node within its immediate transmission range places a packet containing a header with its own and the destination node’s addresses on the RACH queue. The packet is scheduled for transmission over the associated physical random access channel (PRACH), depending on the packet access scheme used for the PRACH.

Every network node must be able to receive RACH packets, since this channel is also used for signalling purposes. Whenever a network device is powered-on, for instance, it has to explore its neighborhood by broadcasting ”hello” messages over the RACH. All stations that are able to receive the ”hello” reply to that message with their own hardware address and other information that may be useful to the new network member. Besides this, the RACH is the means, by which a network node acquires a dedicated channel (DCH) to one of its immediate neighbors. The 802.11 DCF would be an ideal MAC scheme for the RACH.

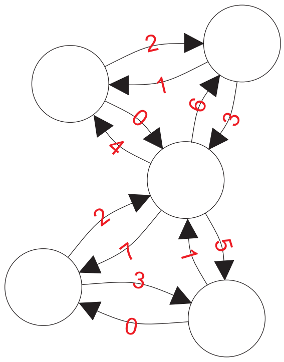

Fig. 2. Results of the DDCA Algorithm

### 2.1.2 Dedicated Channels

Whenever QoS specifications like a bounded delay, low delay jitter, a guaranteed bandwidth etc. need to be fulfilled, a node opens a DCH to one of its neighbors. The DCH is an unidirectional transport channel and maps to a dedicated physical channel (DPCH), e.g. a certain frequency band, time slot and/or code. Mapping to physical channels is done via a distributed DCA (DDCA) scheme.

We have developed a distributed version of the unified DCA algorithm presented in [7], which is able to provide solutions to many assignment problems. The algorithm supports cellular network frequency assignment, TOCA/ROCA/POCA CDMA code assignment, full duplex TDMA or FDMA link schedule/assignment, and many more. In figure 2 a POCA CDMA code assignment is illustrated: CDMA codes are to be assigned to links between nodes such that no two links sharing the same node are assigned the same code. Notice, that this is a simulation result we have achieved with the simulator mentioned below. We have chosen this very simple topology in order to make the results more readable, but we have also successfully run assignments with 100 and 1000 nodes with different node densities.

A duplex channel may be assigned by acquiring a DCH in the reverse direction, where the DDCA algorithm is responsible for selecting the physical channel that creates the least interference, e.g. by choosing another time slot (TDD) or another frequency band, which is far enough apart from the original channel (frequency division duplex, FDD). Using DCHs enables the dynamic creation of virtual circuits, as soon as they are required. The DCH carries pure payload – without the overhead of a packet header that reduces throughput. Therefore DCHs are best suited for lengthy data transmissions and interactive audio/video streams since they support technologies like asynchronous transfer mode (ATM) and symbol stream switching ($S^3$) [9].

### 2.1.3 Mapping Logical Channels to Physical Channels

In our model, we assume that some part of the radio spectrum is assigned as the system band, for instance in the 2.4 GHz or 5 GHz area. This band provides a pool of available physical channels via frequency, time and/or code division. At least one of the resulting physical channels is statically mapped to the RACH, e.g. a certain code sequence in a CDMA system, or a certain frequency band in a FDMA system. This could be a small portion of the spectrum, if the RACH is designated as an out-of-band signalling means only. The other possibility would be to have a high capacity RACH, allowing it to be used for best-effort broadband transport services as well. With prioritization one could guarantee that signalling information is not blocked by this kind of traffic, while at the same time, a lot of capacity could be offered for the exchange of Internet protocol (IP) datagrams of HTTP or FTP connections, for example. In this concept, every subband of spectrum that is not allocated by DPCHs should be assigned to the PRACH. Anyway, this is an open question and part of our investigations.

## 2.2 Synchronization

The next problem to solve is synchronization in the time domain, e.g. to provide a common time base for all network devices. This is necessary because local clocks tend to drift apart by some factor $\rho$, which usually is in the range of $\pm 15 \ldots 500$ppm and stems from the fact that the clocks are usually driven by crystal oscillators with certain tolerances regarding their frequency stability.

### 2.2.1 Centralized Solutions

In networks with centralized management, the base transceiver station (BTS) for a given cell provides some kind of down-link synchronization channel (SCH), through which it periodically broadcasts its own time base to all mobile stations (MS) within the cell. Only under the condition that all devices share the same notion of time, time division multiple access (TDMA) and time division duplex (TDD) are feasible. For instance in GSM networks, the MS transmits three time slots after the BTS, and even the propagation delay is taken into account by means of the so called timing advance (TA). In other words, the MS transmits its data a little earlier as scheduled by the ”three time slots rule”.

With respect to synchronization of BTSs, different concepts are in use. In the European GSM and UMTS systems, BTSs are generally not synchronized – leading to an unsynchronized hand-over when a MS leaves one cell and enters a neighbouring cell. In contrast, the United States IS-95 and cdma2000 BTSs are synchronized, for instance via the timing information provided by the Global Positioning System (GPS). The inconvenience with GPS is the requirement of an undisturbed line-of-sight (LOS) between the satellite and the GPS receiver making it an impractical solution for in-door applications, and thus for most adhoc network applications. Alternatively, the signal provided by long wave transmitters, like the German DCF77, which penetrates most buildings, could be used. Anyway, the proper operation of the communication system would strictly rely on the availability of a third party service, may it be GPS/GLONASS or DCF77 – a dependency that is not desirable in all situations.

### 2.2.2 Distributed Solutions

Obviously, there is no distinction between up- and down-link in a multipoint-to-multipoint system and no single centralized node exists that manages all others. A lot of theoretical and practical work has been contributed to the field of distributed clock synchronization [10] [11] [12] [13] based on the exchange of messages. One example for a distributed algorithm is the 802.11 timing synchronization function (TSF) used in IBSS mode.

### 2.2.3 New approach

When comparing the clock values of two stations at time $t$, say $c_1(t)$ and $c_2(t)$, their difference,

$$\epsilon(t) = c_1(t) - c_2(t) \quad (1)$$

is called *offset*, their frequency difference $\dot{\epsilon}(t)$ is called *skew* and $\ddot{\epsilon}(t)$ is called *drift*. If the clocks are synchronized at some time instant then $\epsilon(t_0)$ equals zero.

Assume that two clocks have been synchronized someway at time instant $t_0$ then $\epsilon(t_0) = 0$. After a short period of time the clocks would begin to diverge because of their skew. Now, if offset, skew, drift, and higher order derivatives of $\epsilon(t)$ were known entities, it would be feasible to run a virtual clock with adjusted frequency. The virtual clock would be able to maintain synchronization with its peer entity for a longer time span and fewer synchronization messages were required to keep $\epsilon(t)$ in reasonable bounds. We propose to use a KALMAN filter [14] for estimation of $\dot{\epsilon}(t)$, $\ddot{\epsilon}(t)$, $\frac{\mathrm{d}^3}{\mathrm{d}t^3}\epsilon(t)$, etc. given only the offset $\epsilon(t)$.

## 3 Software Testbed

Currently, we are developing a network simulator based on a discrete event kernel that allows to test, analyze and optimize the algorithms and protocols we are working on. Key requirements of the simulator are fast processing speed and scalability in order to be able to process networks with thousands of mobile nodes and different kinds of traffic. The development of the simulator will lead to an in-depth and profound understanding of the entire communication network, which is one of the reasons why we have decided to develop a new simulator from scratch instead of extending existing ones, like ns-2 [15], GloMoSim [16], etc. Our goal is to use the same part of C++ source code, both, in the simulations, and in the protocol stack running on real network devices. While the development of the simulator is still work in progress, essential parts have recently been completed [17].

For the modelling of the wireless medium, we have implemented simple free-space and two-ray-ground propagation models, which will be sufficient for our purposes, but more complex fading channel models may easily be added, if such requirements arise. The propagation model computes path loss and propagation delays and implements a link closure model, which is responsible for selecting those receivers that are affected by a transmission. Besides being able to calculate co-channel interference, the simulator is also capable of calculating adjacent channel interference, giving a more accurate result when dealing with FDMA systems. Adaptive antennas are supported as well as multiple receive and transmit channels per transceiver.

At the physical layer, we have implemented a version of the 802.11 PHY, which is interfaced to the wireless medium model. A signal is said to be received successfully, if the carrier to interference plus noise ratio (CINR) exceeds a certain threshold, say 10dB, at the receiver’s site. A model of a drifting clock is also included, in order to support simulation of distributed clock synchronization algorithms.

On top of the PHY, an implementation of the 802.11 MAC handles the delivery of MSDUs and MMPDUs to peer entities. This implementation also supports fragmentation and TX/RX lifetime counters, a feature not seen in the ns-2 and GloMoSim implementations of the 802.11 MAC protocol. We will add the 802.11 TSF in the near future, in order to compare our clock synchronization approach with the current standard.

# 4 Hardware Testbed

Many researchers in the area of adhoc networks use existing wireless LAN network interface controllers (NICs) for validation purposes. These incorporate direct sequence spread spectrum (DSSS) radios that operate on a single channel. Our algorithms, however, are targeted at channel assignment and therefore require a number of channels to be managed, e.g. through FDMA/TDMA/CDMA or combinations thereof.

Thus, we have decided to implement a flexible hardware testbed based on software defined radios (SDRs). In these radios, all functions from modulation to multiple access scheme are programmable and easily modified. There are very powerful (and expensive) commercial system solutions available today. Anyhow, since a number of transceivers are required to establish a network, we have decided to develop our own solution based on standard components including analog to digital converters (ADCs), digital to analog converters (DACs), programmable digital up-converters (PDUCs), programmable digital down-converters (PDDCs), digital filters, field programmable gate arrays (FPGAs) and digital signal processors (DSPs). Many of the leading chip manufacturers in this area provide products and evaluation boards: Analog Devices, Intersil, Graychip, Texas Instruments, Xilinx – just to mention a few.

Figure 3 outlines the proposed architecture for the radio prototype. Right now, we are in the phase of component evaluation and selection. The radio frequency (RF) front-end consists of the antenna, duplexing unit, high power (HPA) and low noise (LNA) amplifiers, fixed local oscillators (LOs) and analog mixers for the receive and transmit paths, which are used to convert the system band to the intermediate frequency (IF) where the transition to the digital domain occurs. One or more channels are then selected via a PDDC (receive path) or combined via a PDUC (transmit path) so that the DSP has to cope with the reduced base band data rate only. Most PDDCs/PDUCs support more than a single channel, they are available as single/dual/quad channel versions, for instance. This way, multiple input streams from different transmitters can be received simultaneously and it is also possible to transmit on a number of channels at the same time. The DSP is basically responsible for line coding and modulation, the FPGA could perform link framing, channel coding, and run parts of the MAC and LLC finite state machines (FSMs), etc. Other parts of the LLC could run on the micro controller ($\mu$C) or micro processor ($\mu$P) of the host system together with the network protocol and the target applications.

# 5 Conclusions

Wireless adhoc networks represent a challenging field of research in the domain of communication networks. Essential features and problems, which are not known from classical hierarchically organized structures, have been discussed, since they require new concepts in particular with respect to the first three layers of the ISO/OSI reference model.

First concepts for the design of logical channel architectures and synchronization mechanisms have been presented. Finally, a network simulator based on a discrete event kernel has been introduced and compared to software developed at other universities. Obviously, most problems arising with adhoc networks represent still open fields of research. The concepts introduced in this paper are the starting point for future work.

*References:*


[1] C. R. Lin and M. Gerla, "Real-time support in multihop wireless networks," *ACM-Baltzer Journal of Wireless Networks*, vol. 5, no. 2, 1999.

[2] Z. Haas and S. Tabrizi, "On some challenges and design choices in ad hoc communications," in *Proceedings of the IEEE Military Communications Conference (MILCOM '98)*, Boston, Oct. 1998.

[3] S. Ramanathan and M. Steenstrup, "Hierarchically-organized, multihop mobile wireless networks for quality-of-service support," *ACM-Baltzer Journal of Mobile Networks and Applications*, vol. 3, no. 1, pp. 101–119, June 1998.

[4] M. Steenstrup, "Dynamic multipoint virtual circuits for multimedia traffic multihop mobile wireless networks," in *Proceedings of the IEEE Wireless Communications and Networking Conference (WCNC '99)*, New Orleans, 1999.

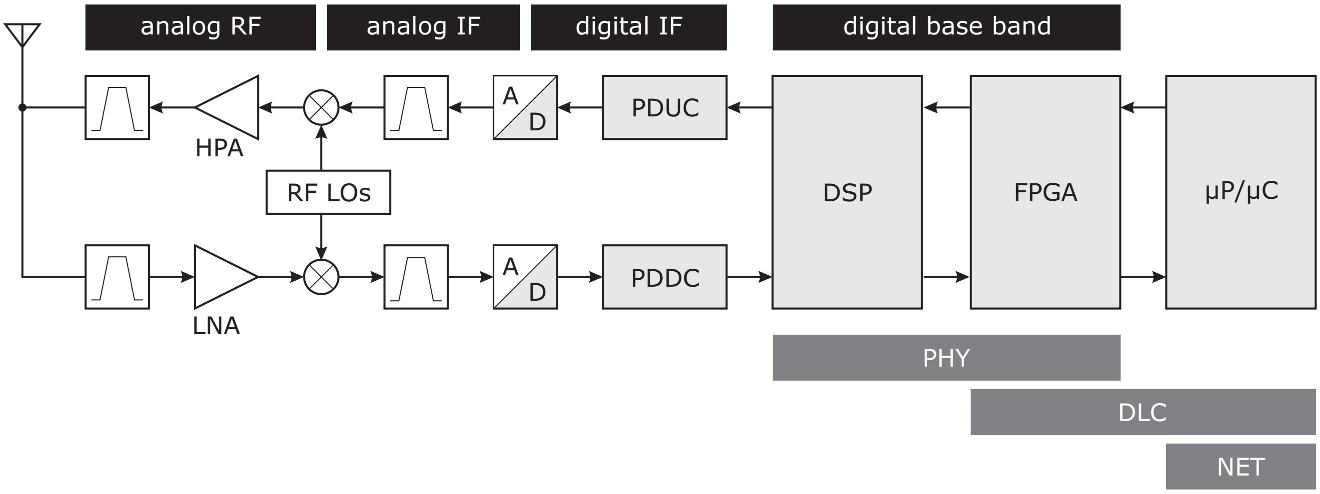


Fig. 3. Proposed Radio Architecture


[5] ANSI/IEEE Standard 802.11, *IEEE Standard for Information technology - Telecommunications and information exchange between systems - Local and metropolitan area networks - Specific requirements. Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications*, ISO/IEC 8802-11:1999(E).

[6] S. Ramanathan and R. Rosales-Hain, "Topology control of multihop wireless networks using transmit power adjustment," in *Proceedings of the IEEE Conference on Computer Communications (INFOCOM)*, Tel Aviv, 2000, pp. 404–413.

[7] S. Ramanathan, "A unified framework and algorithm for (T/F/C)DMA channel assignment in wireless networks," in *Proceedings of the IEEE Conference on Computer Communications (INFOCOM)*, Kobe, Japan, Apr. 1997, pp. 900–907, Also appeared in ACM-Baltzer Journal of Wireless Networks, 5 (1999), pp. 81–94.

[8] S. Ramanathan and E. L. Lloyd, "Scheduling algorithms for multihop radio networks," *IEEE/ACM Transactions on Networking*, vol. 1, no. 2, pp. 166–177, 1993.

[9] W. Hoseit and H.-J. Meckelburg, *Data Transmission System with Relay Stations between a Source Station and a Target Station*, World Intellectual Property Organization, 1999, International Patent No. WO99/12279.

[10] B. Patt, *A Theory of Clock Synchronization*, Ph.D. thesis, Massachusetts Institute of Technology, Oct. 1994, MIT/LCS/TR-680.

[11] F. Cristian and C. Fetzer, "Probabilistic internal clock synchronization," in *Proceedings of the Thirteenth Symposium on Reliable Distributed Systems*, Dana Point, Oct. 1994, pp. 22–31.

[12] D. L. Mills, "Improved algorithms for synchronizing computer network clocks," *IEEE/ACM Transactions on Networking*, vol. 3, 1995.

[13] R. Ostrovsky and B. Patt-Shamir, "Optimal and efficient clock synchronization under drifting clocks," in *Symposium on Principles of Distributed Computing*, 1999, pp. 3–12.

[14] R. E. Kalman, "A new approach to linear filtering and prediction problems," *Transactions of the ASME: Journal of Basic Engineering*, vol. 82(1) D, pp. 35–45, Mar. 1960.

[15] K. Fall and K. Varadhan, Eds., *The ns Manual*, The VINT Project (UC Berkeley, LBL, USC/ISI, and Xerox PARC), Aug. 2000, Available at `http://www.isi.edu/nsnam/ns/ns-documentation.html`.

[16] X. Zeng, R. Bagrodia, and M. Gerla, "GloMoSim: A library for parallel simulation of large-scale wireless networks," in *Proceedings of the 12th Workshop on Parallel and Distributed Simulation*, Banff, Alberta, Canada, May 1998, pp. 154–161, ACM.

[17] A. Honarbacht and A. Kummert, "WWANS: the wireless wide area network simulator," in *Proceedings of the International Conference on Wireless and Optical Communications (WOC2002)*, Banff, Canada, July 2002.