Communicating Personal Gadgets

Hans Scholten, Pierre Jansen, Laurens Hop
University of Twente, Department of Computer Science (EEMCS), Enschede, the Netherlands
Email: {scholten, jansen, hop}@cs.utwente.nl

***Abstract*— This paper focuses on communication in personal area networks. A personal area networks (PAN) is characterized as an informal collection, or community, of connected small, lightweight, and resource-lean devices, or gadgets. Two basic concepts are visible in the development of PANs, the distributed and the centralized concept. The paper introduces a real-time communication protocol that is suitable for both concepts. The communication protocol can deal with several types of traffic: real-time or non-real-time, bursty or isochronous, high or low bitrate. The protocol is undemanding in terms of resources, so even simple devices can participate in the network. The network is simulated and a prototype is realized.**

***Index Terms*— Personal area network, QoS support, real-time network, wireless network, medium access protocol, community**

I. Personal Area Networks

Personal area networks (PANs) can be defined as a collection of portable devices that temporarily meet to accomplish a common task for their owners. This collective, or community, can take many forms, depending on context and setting, private or public: people and devices exchanging information among themselves or with their surroundings. Communities are not to be confused with the traditional collaborative systems where people share data and knowledge in a virtual world. A community exists in the real world, sensing real world data and acting in the real world.

Characteristics of a community are:

- *instantaneous*: spontaneous and autonomous on the spot networking without help of a network operator;
- *dynamic*: the network is in principle open and anyone who is authorized may join;
- *ubiquitous*: networking is available anywhere and anytime;
- *collaborative*: the network is assembled on a need-be basis to accomplish some kind of collaboration or cooperation between the members of the community.

This work is sponsored by the Netherlands Organization for Scientific Research (NWO) under grant number 612.060.111, and by the IBM Equinox programme.

A PAN has to support different types of devices, each with its own characteristics:

- *entertainment*: usually isochronous streaming media based devices, like mp3 player or digital movie camera. Such a device requires a high bandwidth and real-time responses;
- *command and control*: sensors and actuators, like GPS or blood pressure sensor. These devices use or generate low bandwidth data. C&C devices generally need real-time dependable services;
- *information*: traditional PDA and Internet application based devices. Network traffic is bursty and normally needs only best effort responses.

Other challenges must be faced by PANs as well:

- *compatibility and interoperability*: appliances are connected and have to work together. So they must ‘speak’ the same (sub-)set of protocols;
- *data compatibility*: the appliances must all be able to work on the data in the network. E.g. it should not matter on which device someone listens to pre-recorded music. So data formats for different devices must be compatible or must be converted on-the-fly;
- *resources*: a network often covers both resource-lean and resource-rich devices (in terms of CPU, memory, power, size). All are connected to the network and must be able to work together, regardless of resources;
- *ad hoc configuration and service discovery*: a domestic network is dynamic. Devices are connected to the system and removed again. It would be undesirable to configure the system by hand every time this happens, the system must configure itself automatically.

HAVi [1], Jini [2] and Universal Plug-and-Play [3] are just a few examples of initiatives that try to solve these challenges for domestic networks. They use different types of network, wireless and wired, but often lack real-time behaviour, or require substantial resources, or are suitable only for just one type of application. In general, this makes these systems unsuitable for *integrated* networks for use in PANs.

Fig. 1. Ad hoc network example

As defined before, a personal area network is a collection of personal gadgets that communicate to accomplish a common task for its owner. Sometimes this collection will communicate with its surroundings — house, car, shop, museum, or another collection of PGs. In this context two diverging trends, which have implications for the communication structure, are visible.

A. Multi-Function Devices

This trend is characterized by ”heavy” devices that integrate a multitude of functions, e.g. a mobile phone, which doubles as a notebook, calendar, calculator, game machine and mp3 player. Probably the user of such a device possesses other devices as well, such as a digital camera, or a PDA. Even if these devices can communicate together, there is still little or no integration or interoperability. When the camera is out of memory, it is not possible to make additional photos, even if the mp3 player has memory left. See figure 1. This example also shows that there is overlap in functions. All devices have memory of their own, which can not be shared. There is other overlap as well, like the PDA-like function in the mobile phone and the PDA. An advantage of all-in-one devices is that they can work stand-alone without being dependent on other devices.

B. Single-Function Devices

The new trend is single-function ”light-weight” devices that can communicate together and complement each other. The system consists of one base station with basic functionality, complemented by small devices. The base station is called the ”personal mobile gateway” or PMG. An analogy might be the image of a central computer surrounded by its peripherals. The PMG provides processing power, storage and a gateway to the outside world for the rest of the PAN. In the view of IXI [4] internal communication is by means of Bluetooth [5]. Communication with the outside world is through a cellular network modem. IXI claims the following benefits of the concept:

- increased variety of devices;
- devices have faster time to market;
- devices are easy to design and manufacture;
- lower cost;
- applications can run on the PMG, saving memory cost and processing power.

The only device able to function stand alone is the PMG. All other devices need at least the PMG to function properly. E.g. the digital camera can take a picture, but has no memory to store it. The PMG can be a dedicated device on its own, but it can also be integrated in one of the peripherals. Because it is a device most people always carry, the mobile phone is a probable candidate to function as PMG. More than in a network of heavy devices, a PMG based system depends heavily on the network, because all information must be offloaded to the PMG or vice versa. This network should be high bandwidth and real-time as it has to cope with – among other types of data – video and audio streams.

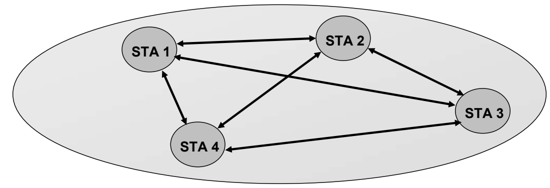

Fig. 2. Ad hoc fully connected network

II. Mapping Communication Models

The two concepts for personal area networks described in the previous section have to be mapped on a network model. Three basic communication models are important in this context:

- ad hoc communication fully connected;
- ad hoc communication with hidden nodes;
- managed communication.

A. Ad Hoc Communication Fully Connected

This communication model knows no centralized authority and assumes that every node is able to communicate directly with every other node in the network. This is shown in figure 2. Every communication is only one hop long and a broadcast will be received by all nodes.

B. Ad Hoc Communication with Hidden Nodes

As in the previous model this model has no centralized authority. However, in this model hidden nodes may be

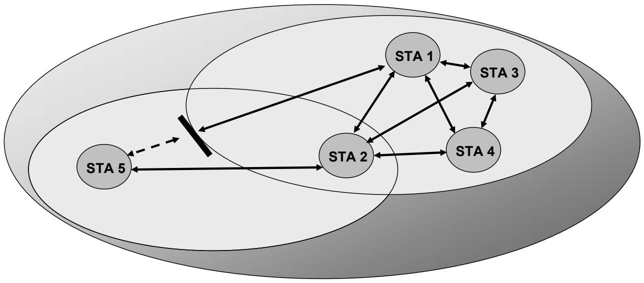

Fig. 3. Ad hoc network with hidden nodes

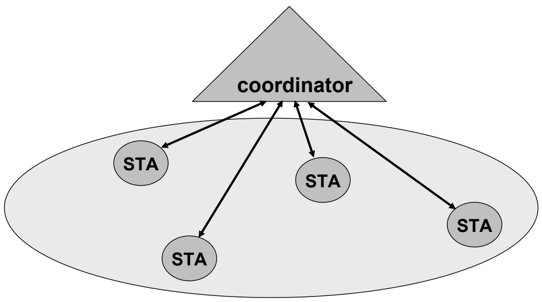

Fig. 4. Managed network

present. A hidden node is a node that is only visible by a subset of the nodes in a community. This is illustrated in figure 3. In this case node STA 5 is a hidden node and is only visible to node STA 2. STA 5 has always to communicate via STA 2. Thus STA 5 is one hop away from STA 2, but from STA 1, 3 and 4 it is two hops away. Assuming that a simple transfer of data in the fully connected model has a delay of τ, whenever STA 2 is relaying, a transfer has a delay of $2 \cdot \tau$. The reason is that STA 2 is visible by all nodes. Consequently when STA 2 sends, its transmission is received by all nodes. So STA 2 can not send to STA 5 when another node is sending and has to wait for the other node to stop its transmission.

C. Managed Communication

The managed network is, like the first model, a fully connected network. In this case this is achieved by communication via a centralized authority that is visible to all nodes. Communication between two nodes has always a delay of $2 \cdot \tau$. See figure 4.

D. Mapping Multi-Function Devices

Although the managed network model can be used, the most natural model for a personal area network consisting of ”heavy” multi-function gadgets is the ad hoc network model. The gadgets have all the resources on board to function stand alone and they do not rely on other devices, e.g. the digital camera does not need other devices to take and store a picture. The network function is in most cases used to upload or download content and not for distributed or collaborative work. The mobile phone and the notebook are in this view the most central devices. The mobile phone is used to connect other devices with the outside world via GPRS or UMTS, while the notebook is used to connect to a backbone network or to store content (Figure 1). But despite these functions, the phone and notebook are mere peers in the system. Even though they have a central function, like the traditional gateway, they do not coordinate the PAN.

E. Mapping Single-Function Devices

Because a collection of single-function devices in combination with a personal mobile gateway has a logical natural order, the managed network model seems appropriate. The PMG is the centre of things and the gadgets rely on it to function properly. This model, as observed before, has the disadvantage that communication delays between two gadgets is $2 \cdot \tau$. In spite of this disadvantage it is a suitable model. An alternative is the ad hoc fully connected model. The PMG is always reachable in one hop by any gadget and gadgets can communicate mutually in one hop without de need for the PMG to relay messages. Communication delays are always one τ in this model. The ad hoc model with hidden nodes is less suitable. Because a communication can be multi-hop delays can become unacceptable long. Messages need to be relayed by the gadgets and have to be stored in the relaying gadgets. With high bandwidth streams the need for buffer capacity can be demanding. In addition routes through the network must be calculated and routing tables have to be kept. Instead of ”lean” devices this requires full-fledged ones, which contradicts the concept of single-function devices.

Figure 5 summarizes the best mappings of devices on network models.

Type	AH FC	AH HN	Managed
MF	•	•	–
SF	•	–	•

AH FC: Ad Hoc Fully Connected
AH HN: Ad Hoc Hidden Nodes
MF: Multi-Function Device
SF: Single-Function Device

Fig. 5. Summary network mapping

III. Real-Time Communication

In the previous sections we have described the types of data in a PAN – such as real-time, dependable and

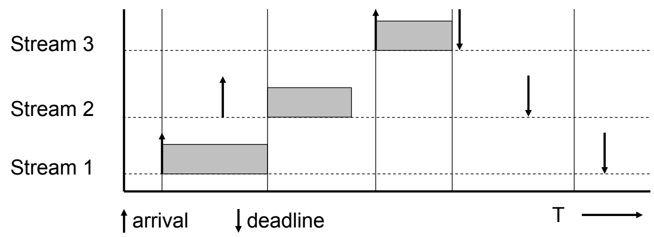

Fig. 6. Example of EDF schedule

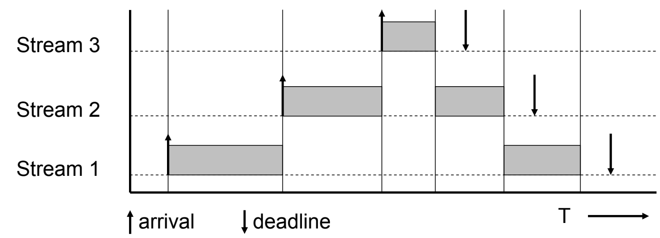

Fig. 7. Example of PEDF schedule

isochronous information – and given a mapping of device types in a PAN on a network model. Now we introduce a network protocol for PANs that supports these data types that can be used in the network models.

A. Single-Hop Network Scheduling

Malcom and Zhao [6] and Sevcik and Johnson [7] describe real-time networks, like IEEE802.4 token bus, IEEE802.5 token ring and FDDI, that are based on passing around tokens. The token visits the nodes in the network according to a simple scheme, such as round robin. When a node receives the token it is allowed to use the network during a predefined time, the token holding time or THT. This THT may be different for different nodes. Even if a node has nothing to send it will get the token during a round, which may lead to considerable loss of bandwidth.

We have proposed a more advanced way to direct the token in the network [8] [9]. Here the token is scheduled based on a variant of earliest deadline first (EDF) scheduling (See [10]). An example of a non-pre-emptive EDF schedule is shown in figure 6. The figure shows the schedule of three streams, each with an arrival time (↑) and a deadline (↓). When a stream arrives it has to wait till the current stream ends. Then the stream with the earliest deadline is allowed to use the network. Stream 2, although it has an earlier deadline than stream 2, has to wait till stream 1 is ready sending. The variant of EDF used for the token is pre-emptive earliest deadline first (PEDF) scheduling. In this variant new arrivals with an earlier deadline than the current stream do not have to wait till the current stream is finished. The current stream is pre-empted in favour of the new stream. When the new stream ends, the previous stream is restored. This is shown in figure 7. Stream 1 is pre-empted by stream 2, which in turn is pre-empted by stream 3. It is presumed that the streams are periodic – the figure shows one period – where each stream may have a different period.

The scheduler that calculates the schedule can be distributed or reside in a single node. The current prototypes use a distributed scheduler, meaning that each node in the network has a resident scheduler to calculate a new schedule when this is needed. Schedule information is passed on via the token. This type of scheduler can be used in both ad hoc and managed network models, but is most suitable in the ad hoc variant. The centralized scheduler can be used in the managed network model, where the PMG can calculate and give out the token to the gadgets. This saves some token overhead and makes the gadgets even leaner. We have shown that this principle is applicable as well for normal access points in IEEE802.11 networks, as is described in [11].

Any stream that is accepted in the network must be dependable, it must keep its deadlines and it should not be interrupted by other streams. The PEDF scheduler can guarantee this if the total of streams does not exceed the network's capacity, or else a schedule can not be calculated. Before a new stream is admitted to the network, the system must check whether the new set of streams is feasible. For PEDF this is a simple check. Under the assumption that a stream's period is equal to its deadline, a set of periodic streams is schedulable with PEDF if and only if

$$\sum_{i=1}^{n} \frac{B_i}{B} \leq 1$$

Where
n: Number of streams;
B_i: Bandwidth of stream i;
B: Maximum bandwidth of the network.
When the streams in the network meet this requirement, the PEDF scheduler will find a schedule. PEDF has the nice property that it gives 100 percent utilization of the network bandwidth. A disadvantage is that performance collapses in case the network is overloaded. This, however, is avoided, because every time a new stream is added or an existing stream changes, the feasibility of the new set of streams is checked. Only if the set of stream is schedulable, i.e. there is no overload, the new set is accepted.

The network and its PEDF token mechanism are simulated and prototypes based on Ethernet and IEEE802.11b are built. Figure 8 shows simulator output for the PEDF

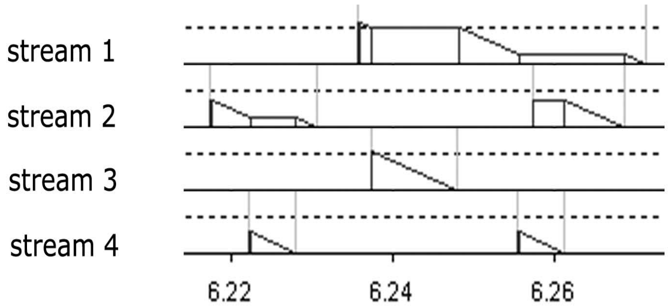

Fig. 8. PEDF schedule of a set of periodic streams

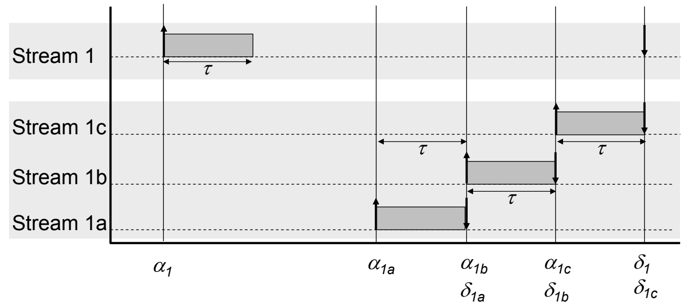

Fig. 11. Multi-hop (ultimate) PEDF schedule

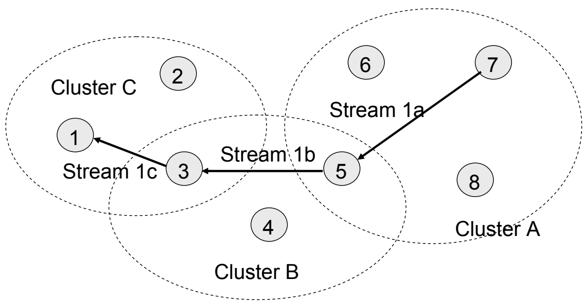

Fig. 9. Example of a multi-hop network

scheduling of a set of periodic streams. The graph shows the remaining amount of data to be sent by a stream during that period. When the stream is transmitted this line decreases linearly with the number of bytes sent. A horizontal line shows where the stream is pre-empted by another stream. A rising edge of a stream is the arrival time of a period and is equal to the deadline of the previous period. The time between two rising edges of a stream equals one period of that stream.

B. *Multi-Hop Network Scheduling*

The principle of single-hop network scheduling is extendible to multi-hop networks. In the example of figure 9 a (periodic) stream from node 7 to node 1 is relayed by two intermediate nodes – 5 and 3 – in the network. The network is divided in three clusters, where every cluster is a fully connected (sub)network. Some

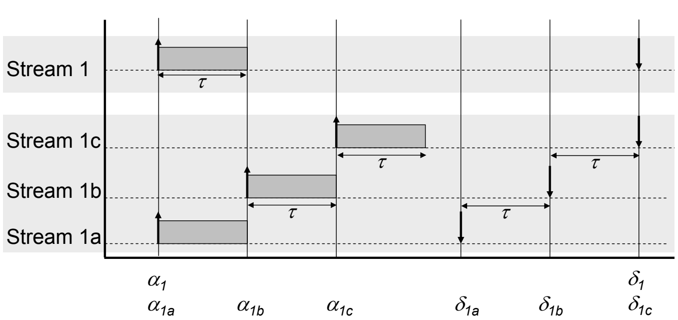

Fig. 10. Multi-hop PEDF schedule

nodes are in more than one cluster, which makes them potential relays for transmissions from one cluster to an other.

When a node is sending, in most technologies, it is deaf for transmissions from other nodes. As a consequence nodes can not send and receive at the same time. When a node in a cluster is sending, no other node in the same cluster is allowed to send, or else both transmissions will interfere. So, in our example, when node 7 is sending no other node in cluster A may send. Because node 5 is in both clusters A en B, and it must be able to receive from node 7, no other node in cluster B may send. Nodes in cluster C which are not in cluster B may send however. When node 5 is sending no node in cluster A or B may send. But also no node in cluster C may send, because node 3 must be able to receive from node 5. Similarly, when node 3 sends, no other node may send. Thus, depending on the particular configuration of the network, some parallelism can exist between clusters. However, because of its relatively small size, the number of clusters in a PAN is limited and it is plausible that no parallelism exists at all.

For the example (figure 9) this means that the stream is divided in three sub-streams, and that each frame of the stream will be transmitted one after the other. This is shown in figure 10, where one period of the stream is shown with an arrival time α_1 and a deadline δ_1. Sub-stream 1_a has the same arrival time α_{1a} as stream 1, and sub-stream 1_c has the same deadline δ_{1c} as stream 1. Because stream 1_b has to be received by node 3 before stream 1_c can be sent by the same node, the deadline δ_{1b} of stream 1_b equals the latest possible arrival time α_{1c} of stream 1_c:

$$\begin{array}{ll} \alpha_1; \delta_1 & (stream1) \\ \alpha_{1a} \geq \alpha_1; \delta_{1a} \leq \delta_{1b} - \tau & (stream1_a) \\ \alpha_{1b} \geq \alpha_{1a} + \tau; \delta_{1b} \leq \delta_{1c} - \tau & (stream1_b) \\ \alpha_{1c} \geq \alpha_{1b} + \tau; \delta_{1c} \leq \delta_1 & (stream1_c) \end{array}$$

Figure 10 shows the earliest possible scheduling of the substreams, and figure 11 the latest possible scheduling. The scheduler has to ensure that stream 1_a is transmitted before stream 1_b, and stream 1_b before stream 1_c. This is guaranteed by the PEDF scheduler when:

$$\alpha_{1a} \leq \alpha_{1b} \leq \alpha_{1c}$$
$$\delta_{1a} < \delta_{1b} < \delta_{1c}$$

The limits for α's and δ's for the sub-streams meet these requirements.

Because the network has to accommodate three sub-streams instead of one stream, where each sub-stream has the same bandwidth requirements as the original stream, the total requested bandwidth is three times the original bandwidth. More general, a set of streams, where each stream i is composed of s_i sub-streams, is feasible if and only if

$$\sum_{i=1}^{n} \frac{s_i \cdot B_i}{B} \leq 1$$

Where
n: number of streams;
s_i: number of sub-streams in stream i;
B_i: bandwidth of original stream i;
B: Maximum bandwidth of the network.

This token scheme is applicable to both ad hoc and managed network models. For the managed network model the number of hops, and the number of sub-streams, is always two. For the ad hoc fully connected network model the number of hops is always one. And for the ad hoc with hidden nodes network model the number of hops is variable, but probably three or less, because of the relatively small size of a PAN.

IV. Conclusion

A personal area network has to be instantaneous, dynamic, ubiquitous and collaborative. It has to support applications in the areas of entertainment, command and control, and information. Depending on which specific applications will be used, the network sometimes has to be dependable and real-time. In this paper we identified two trends according to the type of devices – and philosophy – the PAN is based on: the multi-function and the single function devices. Three suitable network communication models are introduced and a mapping of both trends on these models is given.

The focus of this paper is on a real-time token protocol that is able to support dependable and streaming data in the introduced communication models. The protocol is based on a distributed pre-emptive earliest deadline first scheduler. PEDF guarantees an efficient use of bandwidth, up to one hundred percent. Still the check for available bandwidth, the feasibility analysis, is simple enough to be implemented in small devices. The communication models involve single and multi hop communications. It is sometimes required to use intermediate nodes to relay data from one device to another. We showed how a multi hop stream can be split up in a consecutive sequence of sub-streams, and under which conditions the pre-emptive earliest deadline first scheduling guarantees the necessary order of streams in the network. When these conditions are met, the resulting set of streams can be considered as a ”normal” set of single hop streams and the PEDF schedule can be calculated.

The single hop scheme is simulated and a prototype based on IEEE802.11 is realized. Measurements in the simulation and the prototype showed that pre-emptive earliest deadline scheduling is possible and performs as expected. The PEDF scheduler in the prototype is the distributed version.

Work on a simulation model and a prototype of the multi-hop network has started recently. To accommodate the managed network model a centralized version of the scheduler is planned.

References

[1] HAVi, “Home audio and video interoperability web site,” Website: ‘http://www.havi.org’.

[2] JINI, “Jini homepage,” Website: ‘http://www.jini.org’ or ‘http://www.sun.com/jini’.

[3] UPnP, “Upnp homepage,” Website: ‘http://www.upnp.org’.

[4] IXI, “The ixi web site,” Website: ‘http://www.ixi.com’.

[5] Bluetooth, “The bluetooth special interest group web site,” Website: ‘http://www.bluetooth.org’.

[6] N. Malcom and W. Zhao, “The timed token protocol for real-time communications,” *IEEE Computers*, vol. 10, no. 1, p. 3541, Jan. 1994.

[7] K. Sevcik and M. Johnson, “Cycle time properties of the fddi token ring protocol,” *IEEE Transactions on Software Engineering*, vol. 13, no. 3, pp. 376–385, Mar. 1987.

[8] J. Scholten, P. G. Jansen, F. T. Y. Hanssen, P. H. Hartel, T. Hattink, and V. Sundramoorthy, “Multimedia QoS in low-cost home networks,” in *27th Annual IEEE Conference on Local Computer Networks (LCN)*. Tampa, Florida: IEEE Computer Society Press, Los Alamitos, California, Nov 2002, pp. 327–328, `http:// www.ub.utwente.nl/ webdocs/ ctit/ 1/ 000000a8.pdf`. [Online]. Available: http://www.ub.utwente.nl/webdocs/ctit/1/000000a8.pdf

[9] F. T. Y. Hanssen, P. H. Hartel, T. Hattink, P. G. Jansen, J. Scholten, and J. Wijnberg, “A Real-Time ethernet network at home,” in *Research report 36/2002*, M. G. Harbour, Ed. Vienna, Austria: Real-Time Systems Group, Vienna Univ. of Technology, Jun 2002, pp. 5–8, `http:// www.ub.utwente.nl/ webdocs/ ctit/ 1/ 0000009c.pdf`. [Online]. Available: http://www.ub.utwente.nl/webdocs/ctit/1/0000009c.pdf

[10] G. C. Buttazzo, *Hard Real-Time Computing Systems – Predictable Scheduling Algorithms and Applications*. Kluwer Academic Publishers, 1997, iSBN 0-7923-9994-3.

[11] W. H. Mank and A. Zwikker, “Designing and prototyping the real-time rtnet protocol on wireless lan,” Master’s thesis, University of Twente, November 2002.