Practical Experiences on Mobile Inter-Body-Area-Networking

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ABSTRACT

Body Area Networks (BANs) facilitate a fine grained monitoring of human physical parameters. In current projects, BANs are often seen as single autonomous systems. By allowing BAN-to-BAN communication, information can be piggybacked to other BANs and forwarded to a central server automatically. Besides monitoring of patients, this technology is applicable in many other sectors as well. In this paper we introduce MarathonNet's *pacemate* as the central device of a BAN that supports BAN-BAN and BAN-Backend communication and serves as the BAN-User interface. We present results of our first prototypes and practical experiences on internetworking of 60 mobile BANs during a running competition.

Categories and Subject Descriptors

C.2 [**Computer-Communication Networks**]: Network Architecture and Design; H.4 [**Information Systems Applications**]: Miscellaneous; C.3 [**Special Purpose And Application-Based Systems**]: Real-Time and embedded systems; C.4 [**Performance of Systems**]: Design Studies

General Terms

Design, Experimentation, Measurement, Performance, Reliability

Keywords

Monitoring, Network architecture, Embedded low-power systems, Application analysis, Body Area Network, Internetworking, MarathonNet

1. INTRODUCTION

Driven by the effect of Moore's law the chip size of computer hardware can be divided by two every 18 months with constant performance. Fortunately, this miniaturization often also reduces power consumption, so that cheap and small battery powered computer-based devices are gaining more and more popularity. PDAs and MP3 players are examples of this trend: Available for a few Euros, they perform computational intensive tasks for several hours with a single battery charge.

By equipping these small devices with a wireless communication interface and enabling peer to peer communication, they are able to solve more complex tasks than the sum of the single devices. The research field called *Wireless Sensor Networks* (WSNs) investigates these massive distributed systems with thousands of small nodes additionally equipped with sensing capabilities distributed over a large area [5, 17, 11]. But also in a small area surrounding a person, wireless sensor nodes are advantageous compared to wired solutions and offer potential for new applications in the future with ever decreasing device size.

At first glance, these so called body area networks (BANs) seem to be less complex compared to wireless sensor networks as the number of nodes is smaller, the energy necessary for the wireless communication is lower and the environment of the nodes is managed by the human wearing the devices. But at second glance they impose many practical challenges to be solved prior to their successful application.

We are especially interested in scenarios with internetworking aspects of a huge number of BANs. Therefore we have designed and built a very small and simple BAN device consisting of a single sensor, a data collector and human interface in the first place. We have conducted several real-world deployments where many of these BANs operated in a very dynamic scenario and collected real measured data. Our goal was to better understand the characteristics of the self-forming network.

The rest of the paper is organized as follows. We introduce related work in the next section and conclude that internetworking of BANs in general is not well investigated. In the next section we will provide details of our system components and the envisioned application scenario. For a first evaluation we have chosen a very specific setup that is described in Section 4. Preliminary results and their discussion is given in Section 5. The paper concludes with a summary and directions for future work.

2. RELATED WORK

Today recording and documenting physical parameters finds rising interest mainly in the medical and sports sector. Modern gadgets allow even recreational athletes to keep track of their training. Sports watches equipped with heart rate monitors together with GPS [9] or calibrated pedometers [16] document exercise time, covered distance and physical parameters like the heart rate progression. With provided software, the athlete is enabled to professionally analyze his training. Furthermore, these devices are permanently enhanced and adapted to different sport disciplines.

Aside from these devices that are focused only on the athlete, new wireless technologies allow to involve other groups (such as trainers, supervisors, medical attendants and spectators) and fuel the development of novel applications for new target groups.

The *TinyCoxwain* project [8] uses a wireless sensor network to harmonize a rowing team. Sensors at the boat and at the seats of the athletes transmit the data to the real coxswain and the trainer. The system allows monitoring the performance of the oarsmen and the synchrony among them. In the scope of the project *Dr. Feelgood* [2, 1] a device for evaluating the efficiency of swimming moves was created. Via a radio interface, the acceleration data from different sensors attached to the swimmers body is transmitted to the trainer on the poolside. In [14] acceleration sensors in the boots of professional skiers are used to document parameters which are relevant to the driving style but mostly hidden from the trainer. The data of the sensors is transmitted through a wired connection to a data logger carried by the athlete. Special software allows an analysis of the run based on the recorded data.

Ylisaukko-Oja et al. [18] implemented a wireless body area network with five nodes equipped with acceleration sensors. The system was tested in sports data logging. The sensor nodes are based on their own platform called *SoapBox*. A central node receives the acceleration data from the four remote nodes. Together with its own data the received data is forwarded via RS232 directly or via a serial-to-Bluetooth adapter to a PDA for acquisition. In [7, 6] so called *WiMoCa*-nodes (wireless sensor node for a Motion Capture System with Accelerometers) have been implemented for posture detection. This BAN consists of three WiMoCa nodes where a special gateway node has an interface to a PC or workstation via RS232, Bluetooth or Ethernet. Lubrin et al. [13] implemented a health monitoring system *MoteCare* based on a BAN consisting of Mica Motes [3, 10, 4]. In contrast to the above mentioned architectures the central or gateway node in *MoteCare* is replaced by a personal digital assistant (PDA), realizing the interface between a server for data acquisition and the BAN.

The projects TinyCoxwain and Dr. Feelgood realize a real-time transmission of the data. The trainer receives the data instantly from the sensors. The data is transmitted by the sensor nodes directly (not via other nodes) to the backend, which therefore must be close to the athlete. In the realizations of BANs in [14, 18, 7, 6] data is stored locally in the BAN. It must be extracted manually via RS232 or Bluetooth. This does not allow an online view on the physical parameters. In [13] a PDA is needed to transmit the data on a server.

While the above mentioned approaches focus on the implementation and operation of single BANs as single autonomous systems, the next logical step is the interconnection of different body area networks to form a network of BANs. This allows an automatic transmission of data and a constant monitoring of physical parameters recorded by the BANs. Aside from the health care sector, there are applications in the field of rehabilitation, sports and surveillance of police or fire-fighter units. Another drawback of existing solutions is the user interface, where a standard PDA is used. PDAs are very generic computing devices and with their touch screen not ergonomically well-suited for the above field of application.

Consequently, we will look at BANs and the user interface from the users perspective and propose a new design for a device with adequate simple user interface. In the following section we describe our system architecture and introduce the *pacemate* as the central unit of a BAN allowing the interconnection between different BANs and to a backend system as well as an interaction with the user.

3. ARCHITECTURE AND COMPONENTS

A thorough analysis of the application and the architectural design from the user's viewpoint marked the beginning of our project called MarathonNet. Therefore, we first collected user requirements from an online survey of more than 100 prospective users of the pacemate – our core component for the user and the BAN. The outcome of this survey was matched against the technical requirements and led to the design study shown in Figure 1.

To keep the pacemates as ergonomic as possible, a trade-off between weight, battery lifetime, display size and several other contradicting factors was necessary during the design phase. The pacemates offer an ergonomic waterproof housing, are very light-weight and are easily attached to the back of the hand. They have a large display and sufficient CPU-Power including 32kB RAM and 256kB ROM. They represent the human user interface to the BAN and offer an intuitive operation with three soft buttons. Additionally, they are equipped with three important interfaces:

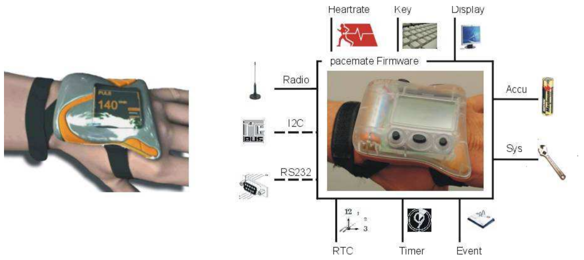

Figure 1: pacemate design study and prototype with interfaces

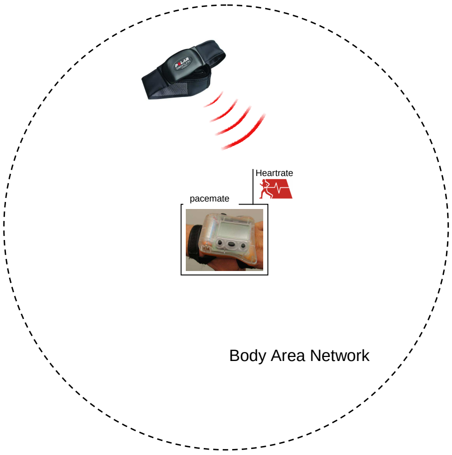

Figure 2: Body Area Network formed by pacemate and Polar chest belt

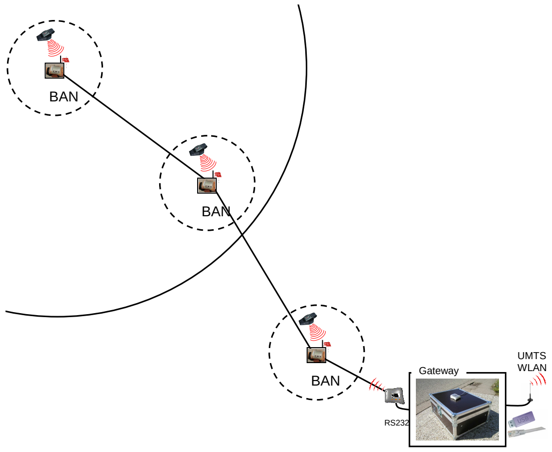

Figure 3: Inter Body Area Networking formed by several pacemates

Figure 4: MarathonNet base station

- serial extension interface for further sensors.
- short range wireless heart rate receiver
- long range wireless interface

The serial interface allows for an extension of the system by additionally plugging in sensors for acceleration measurement, additional vital parameters but also GPS for tracking purpose. This interface is not used so far and is reserved for future use and extension of the BAN.

Pacemates have a built-in short range wireless heart rate receiver. This receiver together with a polar sender in the chest belt as illustrated in Figure 2 form a small body area network. To solve interference of heart rate signals from different users and their disturbance on the heart rate measurement an individual code for the chest belts has been introduced, that is sent along with the heart rate signal. The pacemates synchronize with their chest belt during start up and identify their heart rate signal by ID and proximity.

The pacemates' additional long range wireless interface provides connection via gateways to a backend server to upload and record the monitored data. As shown in Figure 3 pacemates of different BANs build up communication channels to transmit data directly to each other. This communication between pacemates – preferably over several hops – is advantageous when important information will be forwarded directly to the gateway and the backend automatically or if no connection to a gateway is possible piggybacked by others and forwarded to the backend when pacemates get connected to a gateway. This approach will reduce latency and is especially helpful for emergency cases where users vital data is in critical range like heart rate permanently above a threshold without the user noticing this.

The gateways provide as additional components Internet connectivity, though the internetworking of BANs works perfectly without them as well. The hardware is comprised of a pacemate connected via RS232 to a self-sustaining sturdy Linux computer where the received data can be processed and sent on to the backend of the system. In order to keep the backend communication as flexible as possible, we made several interfaces available. Figure 4 shows our current prototype of a base station, including all available interfaces.

The advantage of our current prototype is the flexibility of usage with outdoor capability including a battery enough for 10 hours of permanent operation. For health care scenarios a fixed installed base station with a standard power supply can be much smaller in future. In such a scenario, the base station can be optimized comparable to the size of an off-the-shelf wireless access point with the 802.11x technology today.

4. EXPERIMENTAL SETUP

In order to evaluate our hardware and to gather some real-life data, we deployed our system in Ratzeburg[1] at a 26.1km race. We have chosen this scenario, as a running event offers three key advantages for us. First, runners are very open for new technologies that help them during the race or improve the post-race analysis. Thus, it is easy to recruit hundreds of test persons for an event where more than thousand athletes participate. Second, at the start we will have a huge density of BANs that will decrease slowly during the network life time when the fast runners will be far ahead of the slower athletes. By exploiting this phenomenon, we will be able to investigate the internetworking of BANs with changing network density over time. Third, during the race the runners move along a well defined small track. This effect will lead to a very interesting but well defined scenario where we can reconstruct node constellations post-facto and will be able to analyze these conditions without the need to additionally track 3D node positions. Due to the shape of the runners field, paths with many hops will be plentifully present. Hence, we will be able to investigate protocols working under these special conditions. For a detailed analysis of the network dynamics during a running event, see our recent publication [15].

In Ratzeburg we equipped 58 runners with pacemates and deployed 9 base stations along the track. The data gathered by the BAN is communicated directly or via other BANs to the gateways which pre-process the data and send it on to our backend server that resides on the Internet. The resulting communication setup is shown in Figure 5.

Our system allows us to offer several attractive services to the runner: apart from the current race-time the BAN continuously monitors and saves the runner's heart rate. Furthermore, we are able to show the individual runner his position in the race and the positions of fellow runners. A virtual pacemaker can also be configured in order to assist the runner in meeting his target time. Finally, the gathered data is stored on our backend server to enable the athlete and his trainer to perform a detailed post-race analysis. As a service for the audience and trainers we furthermore made the current positions of the runners available on the internet and displayed them on a video screen during the race.

In order to evaluate the Inter-BAN communication we collected selected statistical data during the race based on the following definitions:

Definition 1 *A link* l_{ij} *is a unidirectional communication channel between two nodes* n_i, n_j ($n_i \neq n_j$)*, where the node* n_i *can directly (not via other nodes) transmit data to the node* n_j*. In our scenario a link between* n_i *and* n_j *is down, when 50 consecutive packets from the node* n_i *were not received by* n_j*.*

Definition 2 *A path* p_{sd} *is a sequence of links* $\{l_{si_1}, l_{i_1 i_2}, ..., l_{i_n d}\}$ *where* n_{i_x} *are called relay nodes. The number of links is called the number of hops and gives the* length of the path. *By definition a link* l_{ij} *from* n_i *to* n_j *is also a path* p_{ij} *of the length 1.*

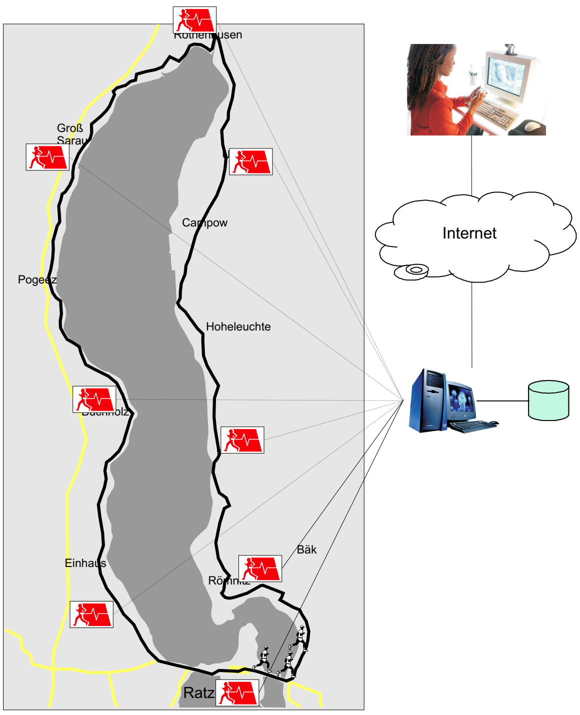

Figure 5: MarathonNet Communication Structure (as deployed around the lake Ratzeburg on the 26.1km track)

Definition 3 *Connectivity between two nodes* (n_i, n_j) *is defined as the condition for which at least one path exists between* (n_i, n_j)*.*

To analyze these parameters, each pacemate initiates a broadcast of an indexed data packet every 250ms in order to test the link quality. On reception of such a packet, a pacemate records data of the received packets for later analysis. With the pacemate memory limitations of less than 20k free memory we need to store the statistics efficiently. Therefore we decided to record only summary information about a link:

source id	the node id of the sender
receive time	the local time of the first received packet
first index	the index of the first packet
last index	the index of the last received packet
received packets	the number of received packets while this link was active

Each pacemate stores the current local time when receiving the first packet of another node. The duration of this link according to the definition above is recorded by saving the first and last received index. Additionally, the number of received packets in total via this link is stored. In order to synchronize all nodes for a detailed evaluation, each node continuously stores the time interval needed to broadcast 50 consecutive packets. By this record we are able to detect bandwidth limitations. When a pacemate is not able to send 50 packets in 12.5s the medium is found busy either with noise or transmissions from other pacemates.

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[1] Located approximately 50km east of Hamburg, Germany

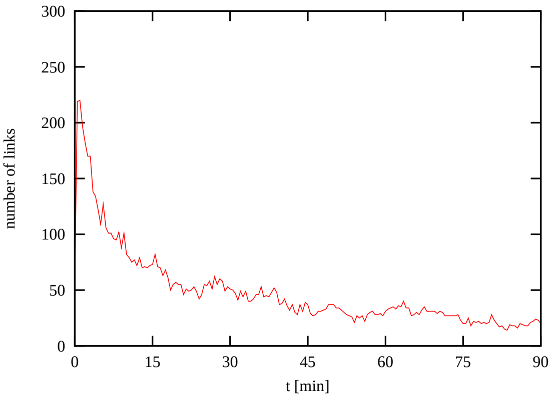


Figure 6: Number of links during the race between the runners equipped with pacemates

5. RESULTS

After the event we evaluated the gathered data collected from the pacemates during the race. We conduct a statistical evaluation comprising a link analysis and the possibilities of multi-hop communication during the race. Furthermore we present our BAN-application from the user perspective.

5.1 Inter-BAN Connectivity Evaluation

In order to evaluate the network topology we analyzed the recorded data during the race. The focus of our evaluation is the connectivity among the BANs and the change during the race. Therefore, we analyze the duration of the links, link symmetry and link quality. We evaluate the existing paths and the resulting connectivity within our network.

To get a perception of network density and dynamics we counted the number of unidirectional links during the network lifetime shown in Figure 6. The initial rapid decrease in the number of links is caused by the quickly decreasing network density. This decrease in network density is the result of the spreading runner field which in turn stems from the different running speeds of the individual athletes. These changes in the density allow us to evaluate the performance of the network under different conditions. Having base stations along the track, we will investigate throughput and algorithms for routing and localization for different application scenarios out of the gathered statistics in future work.

In addition to the number of links, the duration of a link between two nodes contains information about the dynamics in the network. Figure 7 shows the point in time where different links start and the duration, with each bar indicating a single link. The starting time and the duration are depicted along the y-axis. The average duration of a link in this scenario is 60 seconds. A small number of links with very long duration occur in Figure 7. In a post race analysis we verified, that these links belong to runners, who completed the race together.

As the links are unidirectional, we further investigated the link symmetry by comparing links between two nodes. In general links showed to be very asymmetric. In Figure 8, we depicted an extreme example where two athletes run close to each other during the whole race. The left side shows a long lasting link from Node 393 to Node 400. The gaps on the right bar however indicate that for Node 393 links from Node 400 are interrupted from time to time. This example demonstrates that protocols in sensor networks need to cope with asymmetric links and regular link interruptions.

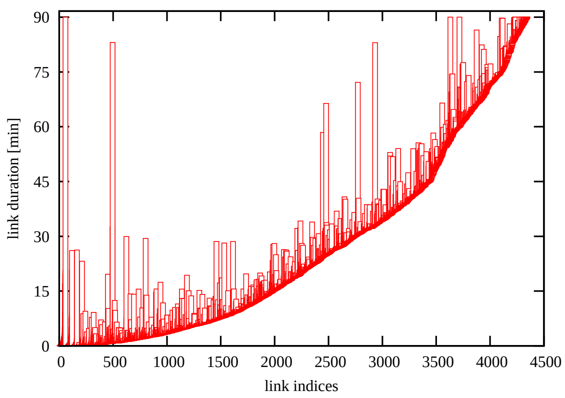


Figure 7: Start time and duration of all links during the race

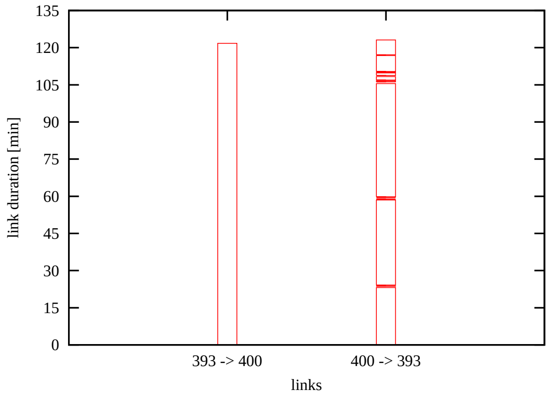


Figure 8: Example of asymmetry of link between Node 393 and Node 400

The link duration shown in Figure 7 and Figure 8 are calculated from the point in time where the first packet is received until the last packet is received. This metric does not include how many packets were not received successfully during this period. Having recorded the first and the last index of received packets from a node as well as the number of received packets, we can derive the quality of a link as the percentage of received packets. Figure 9 shows the quality and the duration of all unidirectional links between pacemates sorted by quality. We can see that one third of the links has a quality of 100 %. The duration of most of these links is within the range of one second and consists of less than a handful of packets. Due to their short length, their duration can not be displayed in the graph. Asides from this, Figure 9 illustrates that in general long lasting links have a better quality than short links as both curves (quality and the peaks for the link duration) decrease together. The weighted average of the link quality is 53 % for all links.

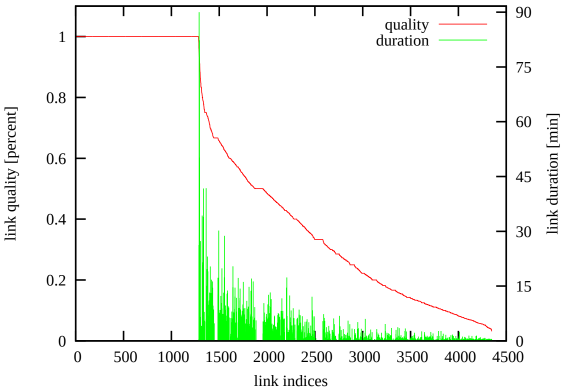


Figure 9: The link quality as percentage of received packets during a link and the corresponding link duration

This clearly demonstrates that packet loss in communication channels for internetworking mobile BANs is a fact. Moreover, almost half of the packets are lost. According to the definition of a link given in Definition 1, the interval for a loss of all packets is limited to 50 packets, which yields with the given transmission rate a gap 12.5 seconds at most with no received packets. Since the position of the runners does not change drastically within this time interval, the low quality cannot be caused by the dynamics among of the runners. Possible reasons for the low quality are:

- packet loss due to shadowing by in-between runners and track characteristics; line of sight is often interrupted
- packet loss by shadowing effects caused by the runners' bodies itself; line of sight only for a short period
- continuous movement of transmitter and receiver due to arm movements of the runners

These observed radio transmission irregularities in a real world scenario are valuable input for the further design of our application. Data propagation strategies and routing protocols must consider continuous packet loss.

As already stated in the introduction, multi-hop forwarding of data improves connectivity between nodes themselves and between nodes and base stations. We have evaluated the factor that we gain for the prototypical setup. Figure 12 shows the connectivity between pacemates during the network life time including multi-hop forwarding. Please note that the shortest path between two nodes may change during the connectivity. We see that the number of all connectivity indices is approximately 15.000. By contrast the number of all links shown in Figure 7 is approximately 4.500. We observe that the number of connectivity indices is three times higher than the number of links. At the time zero the number of links is 200 compared to 1000 paths which results in an improvement of factor 5. In Figure 10 the number of paths during the race is shown. Figure 11 shows the progression of the average path length during the race. Especially in the beginning, the multi-hop propagation provides connectivity between distant nodes.

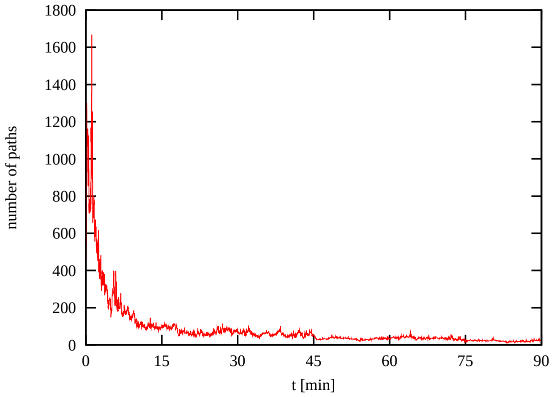


Figure 10: Number of paths between all pacemates during the race

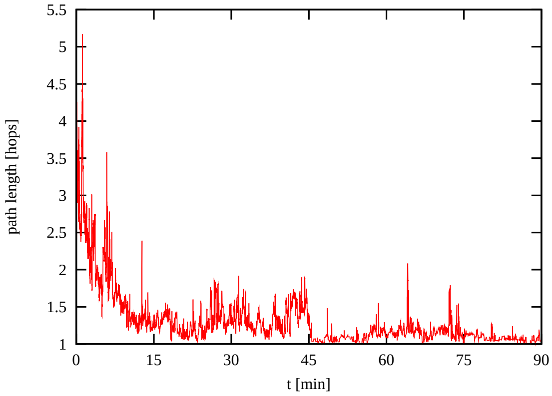


Figure 11: Average length of the shortest paths during the race

Figure 13 shows the almost fully connected network graph at the start of the race. The node positions are only guesses and not based on measurements. This topology will change during the race. Faster runners will separate as the field stretches over the track. We use the measurements as direct input to test algorithms and protocols in simulations. As the network density continuously decreases, we can select the connectivity that we want to investigate from almost fully connected networks of BANs to partitioned networks, with only one test run. On the basis of these results we will determine the optimal conditions and the limits for different algorithms using the simulator shawn [12].

5.2 User Perspective

Apart from technical considerations, a BAN is after all worn by humans. Hence, the devices that form a BAN are subject to the acceptance of their wearers. Consequently, a BAN must be designed with the user in mind. First, it must present a considerable benefit to the user that enhances the users experience in a way that is not achievable with other means. Second, it must be easy to use without intricate configuration and it must be ergonomically designed for mini-

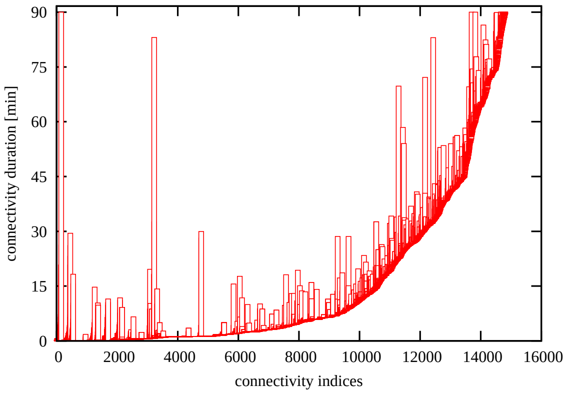


Figure 12: Start time and duration of connectivity for multi-hop

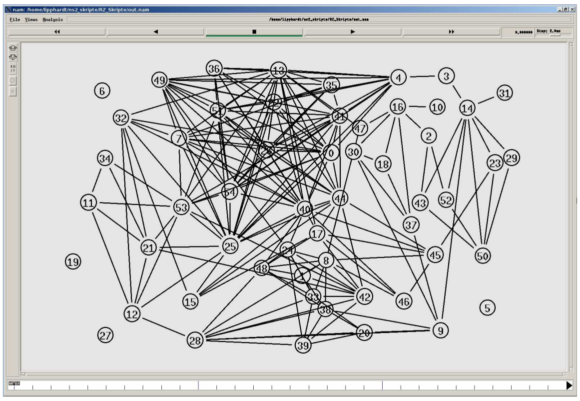
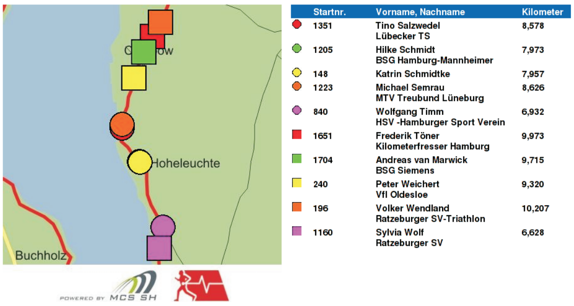


Figure 13: The network structure of Inter Body area networking at start of the race

mal user disturbance.

The pacemate devices were designed from the very beginning with these goals in mind. When interviewed directly after the event in Ratzeburg, runners commended the easy BAN setup and the excellent, direct feedback through the display during the race. This supports our initially stated meaning that pacemates serve as an ideal central device of a single person's BAN. Since sensors that are attached to the user's body are usually not equipped with a user interface (e.g. the chest belt measuring the heart rate), the central device serves as their representative. From our experience, users tend to feel uncomfortable if their physical properties are monitored and recorded without some form of a visual feedback or the possibility of intervention. Thus, we are certain that the visual feedback to the user and the easy interaction using pacemate's buttons are key requirements for a successful BAN application.

By increasing the coverage of the BAN through a long-range wireless interface, the benefit for the users is additionally improved. First of all, as discussed above, the availability of services is raised considerably (in our case by a factor of three) which intensifies the user's satisfaction with the application. In addition, the interconnection with other body area networks yields a variety of further application possibilities that are not possible with only a single BAN. By exploiting Inter-BAN communication, we are amongst other things able to obtain real-time position updates during the race and present them to the spectators as illustrated in Figure 14. The participating runners enjoyed this especially since it increased the experience for their relatives while waiting for their beloved ones at the finishing line.



	Startnr.	Vorname, Nachname	Kilometer
●	1351	Tino Salzwedel Lübecker TS	8,578
●	1205	Hilke Schmidt BSG Hamburg-Mannheimer	7,973
●	148	Katrin Schmidtke	7,957
●	1223	Michael Semrau MTV Treubund Lüneburg	8,626
●	840	Wolfgang Timm HSV -Hamburger Sport Verein	6,932
■	1651	Frederik Töner Kilometerfresser Hamburg	9,973
■	1704	Andreas van Marwick BSG Siemens	9,715
■	240	Peter Weichert Vfl Oldesloe	9,320
■	196	Volker Wendland Ratzeburger SV-Triathlon	10,207
■	1160	Sylvia Wolf Ratzeburger SV	6,628

Figure 14: Visualization of runners during the race

In accordance with our users' reviews, we are convinced that the pacemates are perfectly suited to serve as central BAN device that interconnects a users network with other BANs.

6. SUMMARY AND FUTURE WORK

In our project MarathonNet we will build a large prototypical system with three hundred BANs and ten base stations that provide a connection via a gateway to a central server for data logging and connection to the Internet. The BAN consists of a central device called pacemate for data logging and information processing as well as a dedicated human interface.

Wireless sensors, like a Polar chest belt can be easily integrated into the BAN. We introduced the components of our system and showed the flexibility of the approach. In this paper we focused on the internetworking aspects of our system and presented first measurement results of the internetworking capabilities of approximately 60 preliminary BANs. We showed that multi-hop forwarding of BANs can improve connectivity to a central server by a factor of five at the beginning of the measurement. Furthermore, we evaluated the user acceptance of our pacemate as a key component of the BAN very positively.

Not especially mentioned in this paper, the transmission technology towards the central server proved to be suited even with low GPRS signal levels and low transmission rate for this outdoor experiment. With the recorded transmission statistics and results we will develop protocols in future based on the real transmission characteristics of a measured network instead of artificial radio models. As the density of the network is changing very much over the time of the race we are able to depict a network density of interest by cutting out the interesting interval of the measurements and directly feed our simulations with these statistics. We are currently extending our BANs with additional acceleration sensors to monitor the movement of the users.

7. ACKNOWLEDGMENTS

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