Power- and Delay-Awareness of Health Telemonitoring Services: The MobiHealth System Case Study

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***Abstract*—Emerging healthcare applications rely on personal mobile devices to monitor and transmit patient vital signs to hospital-backend servers for further analysis. However, these devices have limited resources that must be used optimally in order to meet the application user requirements (e.g. safety, usability, reliability, performance). This paper reports on a case study of a Chronic Obstructive Pulmonary Disease telemonitoring application delivered by the MobiHealth system. This system relies on a commercial mobile device with multiple (wireless) Network Interfaces (NI). Our study focuses on how NI activation strategies affect the application end-to-end data delay (important in case of an emergency situation) and the energy consumption of the device (important for device sustainability while a patient is mobile). Our results show the trade-off between end-to-end delay and battery life-time achieved by various NI activation strategies, in combination with application-data flow adaptation for real-time and near real-time data transmission. For a given mobile device, our study shows an increase in battery life-time of 40-90 %, traded against higher end-to-end data delay. The insights of our studies can be used for application-data flow adaptation aiming to increase battery life-time and device sustainability for mobile patients; which effectively increases the healthcare application usability.**

***Index Terms*—mobile device connectivity management, energy efficiency, end-to-end delay, application adaptation, mobile healthcare.**

I. Introduction

THE EMERGENCE of new wireless broadband networks combined with an increased diversity of miniaturized and personalized networked devices give rise to a variety of new mobile interactive applications in our daily life. For example, traditional information consuming mobile applications (e.g. news, leisure and entertainment content delivery) are complemented by information providing mobile applications. Mobile users are no longer only “passive” information or content consumers, but on a growing scale, they take the role of information or content producers; for example, applications that support social interactions between users. Another emerging application domain where users act as content producers is the mobile healthcare domain. In this application domain, a mobile patient’s vital signs are remotely monitored by his healthcare professional in the healthcare centre. In this paper we focus on the healthcare application domain.

The mobile applications are ultimately envisaged to be delivered to a user anywhere, anytime and under different conditions, while fulfilling his Quality of Service (QoS) requirements. These requirements include, for example, low application delay, long device battery life-time and seamless user mobility support along with low monetary cost of networks usage. Because mobile applications operate on a hybrid networking infrastructure, consisting of wireless and wired data communication networks owned by different entities, QoS provided by this infrastructure is one of the most critical factors that influences the application quality provided to the user. In this paper, the quality provided by an application is defined as application-level QoS and comprises *application-level throughput* (in kbps) and *application-level delay* (in milliseconds).

There exists a close relation between application-level QoS and the provided network-level QoS. Particularly, the provided application-level throughput and delay depend respectively on throughput and data transmission delay of the activated (wireless) network interface (NI) of the mobile device. Moreover, the device battery life-time depends on a particular application and activated NI, and the characteristics of the application’s-data flow offered to the NI. Particularly, the application data flow is described in terms of its ’volume’ per time unit; i.e. the size and rate of the data packets offered to the NI in for example bytes per second. By changing the size and the rate parameters, the application-data flow is changed to better suit or even match the provided network-level QoS, and consequently enabling better application-level QoS.

This paper focuses on two main issues: (1) NI activation strategies for the NIs available on a mobile device; and (2) application-data flow adaptation in relation to the energy consumption of the device NIs and application-data delay. The NI activation strategy assumes that a NI can be in an OFF state, ON-IDLE state (NI is connected to a network, but does not send/receive application-data) or ON-ACTIVE

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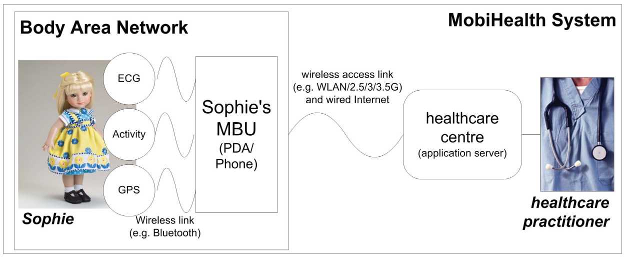


Fig. 1. The MobiHealth system birds-eye view.

state (NI sends/receives application-data). The paper presents results for a mobile application case study, where we show the tradeoffs between application level end-to-end delay and battery power consumed by a mobile device used, through adaptation of application data flow and mobile device NI selection mechanisms.

Mobile applications in the healthcare domain, like telemonitoring or teletreatment [1], [2] pose strict application-level QoS requirements; for example, a patient can be in an emergency situation, requiring an immediate application response (e.g. initiating the dispatch of an ambulance). In this paper, we consider a specific mobile health telemonitoring application: Chronic Obstructive Pulmonary Disease (COPD) telemonitoring application delivered by the so-called MobiHealth system [2].

The rest of this paper is organized in six sections. Section II provides a description of the MobiHealth system. Section III explains our approach towards a mobile device's NI activation strategy. Section IV provides our measurements methodology for energy consumption and application-level delay for a commercial mobile device used in the MobiHealth system. Section V summarizes and analyzes the measurement results, based on which we define the NI activation strategy. Related work is discussed in Section VI. Section VII provides the conclusions and recommendations for the MobiHealth system usage and some future work areas.

II. The MobiHealth system

A. System Overview

The MobiHealth system is a distributed system that can be used for remote monitoring of a mobile patient's health condition.

In the MobiHealth system (Fig. 1), a patient is wearing a Body Area Network (BAN), consisting of one or more sensing devices and a Mobile Base Unit (MBU). A sensing device may consist of specialized sensors that monitor particular vital signs of a patient, or comprise an emergency button that can be pressed by the patient in an emergency situation, or a location sensor (e.g. a GPS receiver) to determine the location of a patient. The sensing devices are represented as a sensor-set which is specific for a patient's health condition. For example health conditions are: respiration insufficiency, cardiac arrhythmia, epilepsy, chronic pain neck-shoulder pain.

The MBU is the central unit of a BAN, usually based on a mobile phone or PDA platform. The MBU has three responsibilities: collection and (time) synchronisation of sensor data, data processing (e.g. signal filtering, deriving vital signs) and sending (processed) data to a remote application backend-server (located in e.g. a healthcare centre). It is specific for the MobiHealth system that all these tasks are performed in real-time. Once the (processed) sensor data has been sent to the backend server, it is made available to other applications; for example, data retrieval, data visualisation or medical decision support applications. Therefore, these applications get near real-time access to patient vital sign data.

The BAN uses an intra-BAN communication network (e.g. Bluetooth) for data communication between sensing devices and the MBU. In addition, the BAN uses an extra-BAN communication network (e.g. WLAN, GPRS and UMTS) for application and control data communication between the MBU and the backend-server.

The application execution is supported by the proprietary MSP-Interconnect Protocol (MSP-IP) [3], a TCP/IP based protocol that facilitates the application data-plane and application control-plane data exchange. MSP-IP and the overall system architecture conform to the Jini Surrogate Architecture specifications as extensively presented in [3], [4]. Interested readers are referred to [2], [5] for a more detailed description of the MobiHealth system and its architecture.

B. Telemonitoring Application-Data Flow

For the purpose of this paper, we consider a telemonitoring application running continuously at the MBU for non-critical COPD patients; i.e., COPD patients with a low probability of getting into an emergency situation. Note that an emergency situation is defined differently for each patient. It is based on the patient's vital signs trend analysis and the detection of dramatic changes. This consideration effects further possible application-data flow adaptation cases (see Section II.C), which will be different for emergency and non-emergency situations.

A sensing device is used in the BAN to acquire the COPD patient's Pulse Rate (PR), oxygen saturation (SpO_2), plethysmogram (pleth) and emergency button. The sensing device has a sampling frequency of 128 Hz and and the sample size is 5 bytes. A data unit collected by the application consists of one second aggregated sensor-set data, in total 640 Bytes. Every data unit is 'deflated' (using a lossless compression algorithm) by the MBU before sending it to the extra-BAN communication network. The data unit compression factor (i.e., the reduction in size relative to the uncompressed size) is 80-85 %. However, this factor strongly depends on the actual values of the measured vital signs; the compression factor decreases as variability in vital signs increases. The MSP-IP introduces 10 Bytes overhead per compressed data unit. Hence, the protocol stack overhead is 64 Bytes for WLAN (MSP/TCP/IP/Ethernet) and 58 Bytes for GPRS (MSP/TCP/IP/PPP). The resulting data unit is sent over the application data-plane. The overall data volume sent by an activated NI comprises of application data-plane and control-plane data (no significant contribution); in total approximately 1.2-1.5 kbps.

C. QoS Requirements

In general, end-users of telemonitoring applications are healthcare professionals and their patients. However, the healthcare professionals define the application QoS requirements [1], [6]. The QoS performance criteria are related to the application-data exchange from the MBU to the backend-server. These criteria are: a) dependability (data transmission availability and loss rate), b) accuracy (error-free data exchange) and c) speed (experienced data delay). The use of TCP/IP in combination with local (at the MBU) data storage ensures application data recovery in case of data loss and encountered data-errors due to poor data communication network performance. Further study of application data communication dependability and accuracy is not the scope of this paper.

Concerning the MobiHealth system's application-data delay requirement, we focus on the extra-BAN communication network and its contribution to the application-data delay. In the MobiHealth system, performance is (partly) managed by means of the application-level Round Trip response Time (AppRTT). The AppRTT is the time it takes for a MBU control message (i.e., MBU Keep-Alive message [3], [4]), to be received by the backend-server and returned back (with minimal processing) to the MBU. The AppRTT reflects the delay induced by the underlying data communication networks and the processing delays in the protocol stacks at the MBU and the backend-server. In particular, the (wireless) access network uplink (MBU to the backend-server) and downlink (backend-server to the MBU) contribute significantly to the AppRTT. Hence, the AppRTT mainly depends on the choice of the extra-BAN communication network (i.e. the activated NI at the MBU) [7], [8].

As we already indicated in the introduction, the considered COPD telemonitoring application delay requirements strongly depend on the actual health condition of the patient. In an emergency situation, patient vital signs data needs to be continuously sent (with the lowest possible delay) to the backend-server in the healthcare centre, where it is made available in real-time to a healthcare professional. For a non-emergency situation, it is possible that the MBU acquires a batch of application-data (both data-plane and control-plane), stores it locally, and sends it later to the backend-server (possibly in bursts); for example, when a cheap (high-throughput) WLAN is available. It is also possible that in a non-emergency situation, the (real-time) BAN data is sent continuously to the backend-server together with historic (i.e. previously stored) BAN data.

Another QoS requirement for MobiHealth is the maximum life-time (i.e. sustainability) of the BAN. In this paper, we focus on the MBU's NI power consumption for extra-BAN communication as the influencing factor to the BAN's life-time. We denote the MBU power consumption as power$_{MBU}$. It depends on the activated NI for extra-BAN communication and the volume of the application-data being sent.

In our study, we also consider an additional user requirement resulting from the patient's need to use his MBU as a regular (i.e., Wireless Wide Area Network, WWAN) phone. Therefore, the patient needs to be WWAN-reachable for voice/data communication, especially with his healthcare professional. Nevertheless, assurance of this requirement may not be favourable from a power consumption perspective, because in this case a WWAN-NI needs to be in an ON-IDLE state continuously, thus consuming power.

In addition, the MBU power consumption depends on many factors, such as the user location/time as well as mobility pattern, the MBU configuration parameters (e.g. backlight brightness), other running applications and MBU location with respect to the wireless network's access point or base station (influences MBU's received signal strength). However, in our study, we consider that a patient (wearing a MBU) is in his workplace. He is mobile in the building, going in between offices, bathroom etc., however he is stationary from the network perspective; i.e. stays in a coverage area of one GPRS cell and one WLAN access point.

III. Network Interface Activation

A. Network Interface State Model

The existing wireless technologies accessible by commercial mobile devices can be divided into two categories: WWANs that provide a low-throughput and high-delay service over a wide geographic area (e.g. GPRS or UMTS) and Wireless Local Area Networks (WLANs) that provide a high-throughput and low delay service over a narrow geographic area (e.g. WiFi) [9]. We consider a NI state model for mobile devices, where a NI can be in one the following states::

- OFF
- ON-IDLE: IP-idle state, where the NI has IP connectivity to the internet; however, it does not send/receive application level data-plane or control-plane IP packets,
- ON-ACTIVE: IP-active state, where NI is sending or receiving application level IP packets through this NI,

The ON-IDLE and ON-ACTIVE states involve some initialization, i.e. datalink/physical-layer level processing and signalling for detection and configuration of NIs (i.e. IP-address acquisition). In our experiments we measure time needed and energy consumed for this initialization.

B. Power Reference Measurements

1) Power Consumption Model: Our data transmission model, used for comparing the efficiency of the basic NI activation strategies in this paper, assumes that a data burst of b bits is transmitted in a maximum transmission window of T_0 seconds. As shown in Fig. 2, T_0 can be divided into T_{act} and T_{idl} periods during which the device respectively sends IP datagrams and remains idle. The model represents the data transmission pattern for a wide range of applications by changing the values of T_{act}/T_0. For example, the ratio T_{act}/T_0 tends to one for media streaming applications and the ratio approaches zero for occasional data exchange. The effective data transfer rate of the model is b/T bits per seconds. Moreover, Fig. 2 indicates a transition period T_{on-off} that is needed to activate and deactivate a NI from OFF state to ON-ACTIVE state and vice versa, which is relevant if the NI used for data transmission is off in the rest of T_0 (in this case Fig. 2 indicates that another NI of the mobile device is in idle state in order for example the mobile device to be always reachable). Fig. 2 shows the average power values consumed in these states by P_{act}, P_{idl} and P_{on-off}. Furthermore, we assume that a NI is in OFF, ON-IDLE and ON-ACTIVE states for durations indicated by T_{act}, T_{idl} and T_{on-off} respectively.

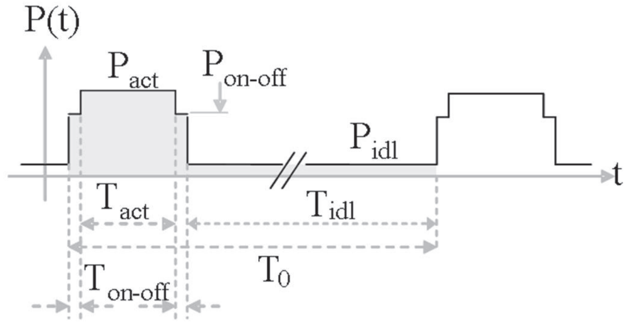


Fig. 2. NI power during data transmission intervals.

2) Measurements Setup: In order to compare the energy efficiency of different NI activation strategies (to be discussed in Section IV.B) based on the presented power consumption model, we first conducted experiments to measure the average power consumption of GPRS and WLAN NIs in OFF, ON-IDLE and ON-ACTIVE states. This section provides a summary of the applied measurement method and the results. The interested reader is referred to [10] for a detailed description.

For our measurements, we used a Qtek 9090 mobile device with Windows Mobile™ 2003 OS and GPRS (GSM 850/900/1800/1900 Hz, class 10: 4+1/3+2 slots) and WLAN (WiFi - IEEE 802.11b, with "best-battery" setting in the OS) NIs. We carried out some experiments to measure the average power consumption of the WLAN or GPRS NI separately, as well as both NIs, in the three operational states OFF, ON-IDLE, and ON-ACTIVE. To put a NI in the ON-ACTIVE state we used the NetPerf tool [11] client (running on the mobile device) to send dummy TCP messages (containing random payload data). In this experiment the WLAN network was configured for the Open System Authentication mode.

To measure the energy consumption we used an OS function every minute to retrieve and record the percentage of remaining battery capacity (i.e. energy). We ran the experiments until either the remaining battery capacity dropped below 25 % or a period of 6 hours elapsed. During each experiment the mobile device was in a steady-state; we have not displaced the device or initiated any other applications. Our objective for running the experiments for maximum 6 hours and in a steady mode was to cancel out energy consumption fluctuations due to disrupting activities originating from the mobile device environment like interferences, sporadic location updates, etc.

In each experiment, the remaining percentage of battery capacity (i.e., the remaining percentage of battery energy) decreased linearly in time. The slope of this linear reduction of battery capacity percentage indicates the *normalized* average power consumed. The resulting average power consumption values are normalized values because the remaining battery capacity was measured in percentage, i.e., it was normalized with respect to the nominal full battery capacity. As the result, the unit of the *normalized* average power obtained is (time-unit) $^{-1}$, which is reported as minute $^{-1}$ or [1/min] throughout this paper. Using these normalized power values was sufficient for our objective of evaluating the *relative energy cost* of WLAN and GPRS NIs in a particular device.

TABLE I
NORMALIZED AVERAGE POWER OF QTEK 9090 NIS

operation states	WLAN (1/min)	GPRS (1/min)
OFF	0	0
ON-IDLE	0.00038	0.00026
ON-ACTIVE	0.00070	0.00077

3) Measurements Results and Analysis: Table I summarizes the values of the normalized average power consumption and the relevant NI states of the Qtek 9090 device. Note that each experiment provided us with the total energy drain rate of the device in a given operational state. We assumed the average power of the device in OFF state as the reference point and subtracted it from each measured average power value: $P_{mode-int} = P^n_{mode-int} - P^n_{off}$. Therefore, Table I indicates power consumption values associated with the NIs. The WLAN and GPRS interfaces, however, send 2 Mbps and 25 Kbps TCP data, respectively. Thus one should keep in mind that WLAN interface consumes much less energy per bit than the GPRS one (almost two orders of magnitude).

To measure P_{on-off} for NI activation strategies we devised a software tool that switches the (only) WLAN NI from OFF state to ON-IDLE state (up to the moment that the NI was assigned an IP address) and switches it immediately to OFF state again. We repeated this operation 3000 times and monitored the rate of battery capacity decrease at regular intervals. The normalized average power consumption of the WLAN NI for this operation (i.e., P_{on-off}) was 0.00054 [1/min]. This is comparable to the ON-ACTIVE state of the WLAN NI as reported in Table I. The average time needed to switch the WLAN NI from OFF state to ON-IDLE and back to the OFF state was 3.83 seconds.

To evaluate the basic NI activation strategies based on power consumption values, we assume the mobile device is subject to the data transmission model described in III.B.1 and we use the normalized average power values of Table I as reference.

C. Delay (i.e. AppRTT) Reference Measurements

In order to compare the delay efficiency of the basic NI activation strategies using the presented application data transmission model, we first conducted experiments to measure the delays observed on the mobile device for GPRS ON-ACTIVE (WLAN OFF) and WLAN ON-ACTIVE (GPRS ON-IDLE) operational states.

This section provides a summary of the measurement method and the results. All measurements have been done at the University of Geneva, Switzerland, as working place for a patient - a MobiHealth system user. The patient is mobile in the building, going in between offices, bathroom etc., however he is stationary from the network perspective; i.e. stays in a coverage area of one GPRS cell and one WLAN access point.

The mobile device uses the Sunrise mobile operator GPRS network (signal strength 100 %) and WLAN provided by the University of Geneva (signal strength 50 %).

In this section, we present typical results for the measured AppRTT when using a specific NI at particular hours of the day and days of the week. It is important to notice that in the rest of this document, for the purpose of document clarity, we only focus on mean values of AppRTT.

TABLE II
APPRTT DELAY HISTOGRAMS DATA SUMMARY

[ms]	mean	std	min	Q25
WLAN	1027	719	224	682
GPRS	2750	911.	458	2239
[ms]	med	Q75	Q99	max
WLAN	836	1111	3320	39476
GPRS	2528	2974	5765	32541

TABLE III
APPRTT DELAY HISTOGRAMS DATA SUMMARY: MEAN (STDEV)

[ms]	Mon	Tue	Wed	Thu	Fri	Sat	Sun
WLAN	1198 (687)	1029 (510)	997 (726)	1011 (640)	943 (904)	N/A	712 (616)
GPRS	2465 (536)	3017 (1075)	2034 (1185)	2335 (452)	2808 (867)	N/A	2658 (779)

We have conducted continuous delay measurements for 26 consecutive days (17 Nov - 15 Dec 2007). Fig. 3 presents histograms for measured AppRTT; the horizontal axis represents the AppRTT in milliseconds and the vertical axis represents the number of observations for a given value. Table II presents the corresponding AppRTT mean and standard deviation values. GPRS has generally a higher mean AppRTT than WLAN. Also its median value is three times higher. In this sense GPRS exhibits longer AppRTT "tail" than WLAN.

Fig. 4 presents AppRTT for WLAN and GPRS along days of the week: Monday to Sunday (Saturday data was not available), see also Table III. From this figure, we conclude that GPRS has a higher mean AppRTT than WLAN. For WLAN, the AppRTT is higher for Monday-Friday than for Sunday (that can be explained that University of Geneva WLAN is not used on Sundays). GPRS exhibits a lower mean AppRTT on Monday and Wednesday, with relatively higher mean AppRTT for other days of the week.

Fig. 5 presents the AppRTT values, i.e. mean $\pm$ stdev, for WLAN and GPRS along hours of the day and days of the week: Monday (1) to Sunday (7) along hours 5 am to 22 pm (data for other hours is not available). The figure indicates that GPRS has a higher mean AppRTT than WLAN. However, there are hours in which both networks exhibit particular AppRTT behaviour. GPRS exhibits steady-state behaviour with occasional AppRTT "deeps" along lunch time (12-14 pm) and dinner time (after 19 pm). We explain this behaviour as follows: it is known from mobile operator's business strategy that GSM (voice) users have priority in using network resources over GPRS (data) users. Hence, when the GSM users are not (heavily) using the network (apparently that happens along meals times), GPRS traffic experiences lower delay in the network. This behaviour has been particularly observed on Tuesdays and Wednesdays. The "around-meal-times" behaviour is also observed clearly for WLAN. Here we see AppRTT "deeps" along lunch time (12-14 pm) and dinner time for Mondays-Fridays. Sunday shows stable AppRTT values as there are not many WLAN users at the University. Moreover, for all mornings and evenings (besides Friday) WLAN exhibits a low AppRTT behaviour.

In contrast, during early-morning hours (6-9 am) GPRS has a high mean AppRTT, which can be explained by heavy network usage for voice communication, when many people start their daily activities. The mean AppRTT value for WLAN is relative high on Friday evening (after 18 pm). This is due to the fact that the University's ICT department schedules network maintenance and data backup activities assuming not many users are using the network.

From the previous AppRTT benchmark measurements for GPRS and WLAN networks, see Section III.B.3, we conclude that besides a different mean AppRTT value for a given NI, networks exhibit clear daily-hourly patterns. In the following sections, we focus on detailed power and delay measurements and previously identified NI activation strategies while using the MobiHealth system.

IV. MOBIHEALTH SYSTEM MEASUREMENTS

A. System Setup

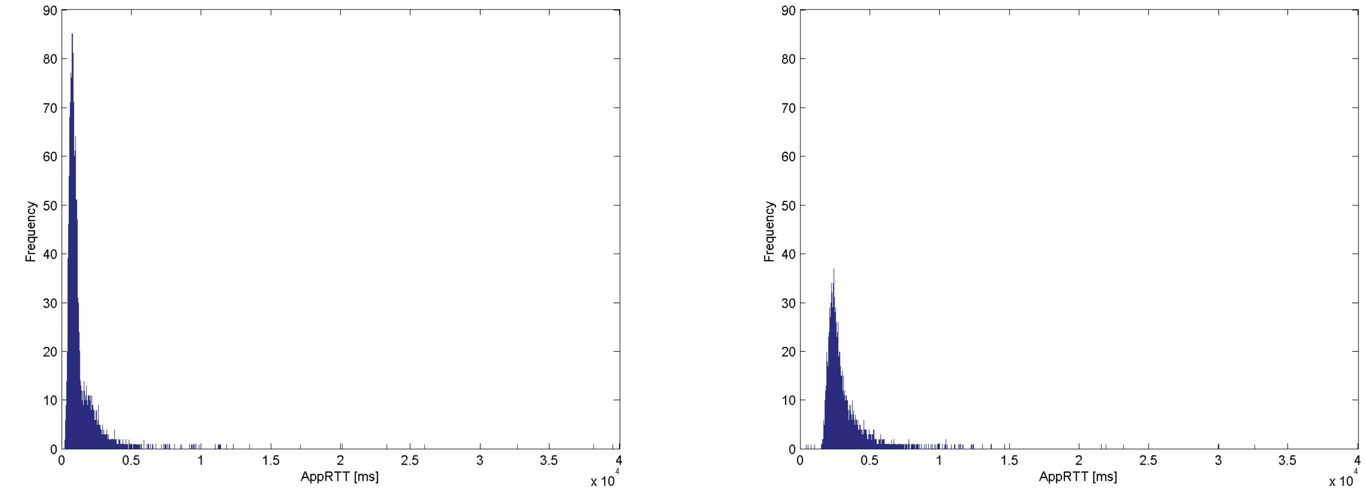
In our research we have made use of a generic measurements-based methodology for performance evaluation of networks, as we have extensively presented in [7], [8]. The MobiHealth sensor system is based on a TMSI Mobi5-3e1as [12]. The attached NONIN pulse-oximeter measures Pulse Rate, oxygen saturation ($SpO_2$2) and plethysmogram. A Qtek 9090 is used as the MBU (as in measurements in section III with an Intel®PXA263 400 MHz processor (32b), 128 MB RAM, firmware version 1.31.00 WWE (from 13.12.2004), radio version 1.06.02, protocol version 1337.38 running Windows Mobile 2003 SE PocketPC OS edition version 4.21.1088. The Qtek uses a rechargeable 1490 mAh Li-ion Polymer battery (3.7V, model PH26B). The Qtek has a TFT touch screen display (width 53mm, height 71 mm; 214 x 320 pixels; 65K colours) of which the backlight level was set to zero.

The Qtek has WWAN-GPRS and WLAN-WiFi NIs for extra-BAN communication. The Bluetooth NI is used continuously for intra-BAN communication to the sensor system for sensor data acquisition. The MBU uses GPRS and WLAN networks in a way, as described in Section IV.B.

The backend-server used is a standard high-performance server dedicated to MobiHealth telemonitoring services. The server was placed at Twente University, the Netherlands. The MobiHealth telemonitoring application software version is a release from 17 October 2007.

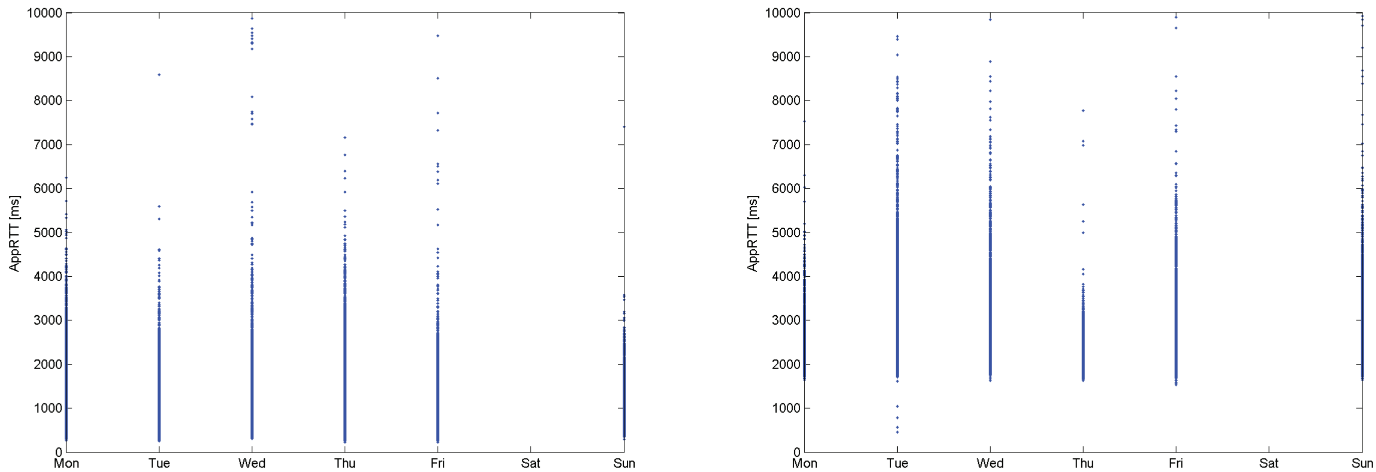
Power and Delay Measurements Instrumentation: The MobiHealth system was configured such that after the execution of the telemonitoring application, we collected the measurements logs from the MBU and backend-server. To measure the energy consumption of the MBU, we logged the remaining battery capacity as a percentage in 5 second intervals. For the purpose of delay measurements, the MBU was instructed to log the AppRTT in intervals of 10 seconds continuously during the telemonitoring application execution.

Obtaining high application-data flow volumes was not feasible with the TMSI Mobi5-3e1as sensor system in the BAN. However, it is important for our measurements of transmitting (high-throughput) data over WLAN NI. We decided to use the NetPerf application. This application generates TCP traffic and measures unidirectional throughput between the MBU and the backend-server. These measurements were done for



(a) WLAN NI (b) GPRS NI

Fig. 3. Histograms of NI delays.



(a) WLAN NI (b) GPRS NI

Fig. 4. NI delays for days of the week.

the same conditions as the other measurements. However, the MobiHealth application was NOT running in conjunction with the NetPerf application. By using this application, we attempted to simulate a case where MBU sends previously stored patient vital signs data. During the NetPerf measurements, we obtained only the power$_{MBU}$ values.

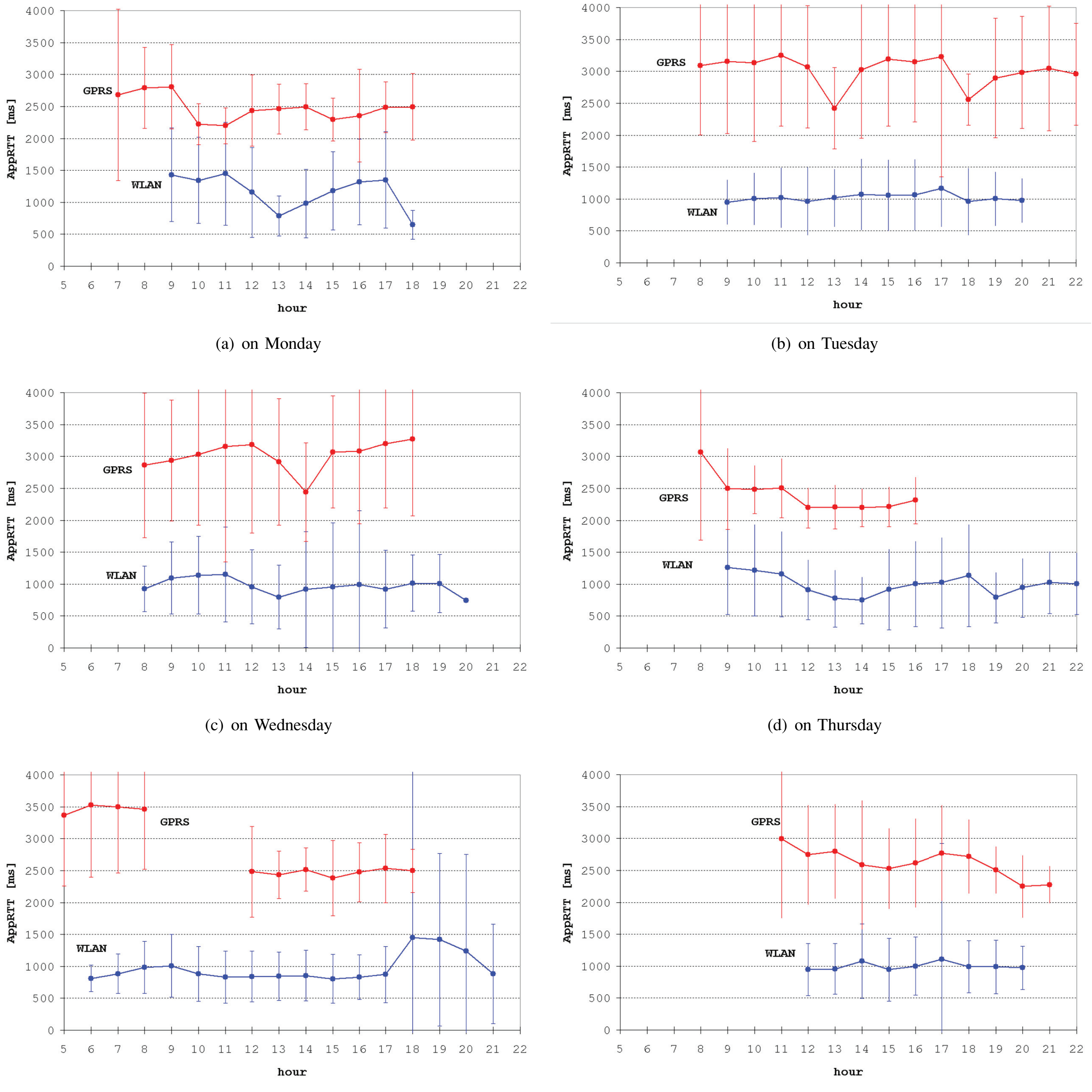
Along the measurements, we assumed the MobiHealth system to be in the steady-state representing the behaviour of the system usage for a typical system user; i.e., a COPD patient, whose vital signs are being monitored. Measurements have been done over a time span of two weeks, always at the same location (University of Geneva office as the working place of the patient using the Mobihealth system) but at different hours.

B. Measurements Cases

From the telemonitoring application perspective the following cases are possible:

1) application-data being sent over the WLAN and GPRS NIs in parallel,
2) application-data being sent via the WLAN NI (ON-ACTIVE state), while the GPRS NI is OFF or ON-IDLE,
3) application-data being sent via the GPRS NI (being in ON-ACTIVE state), while the WLAN NI is OFF or ON-IDLE,
4) application data being stored locally, while the GPRS (and WLAN) NI is in OFF or ON-IDLE.

Note that the activated NI (used for sending data) could be in ON-ACTIVE state continuously or could alternate between



(a) on Monday

(b) on Tuesday

(c) on Wednesday

(d) on Thursday

(e) on Friday

(f) on Sunday

Fig. 5. WLAN and GPRS NI delay for time of week days.

the ON-ACTIVE and the ON-IDLE/OFF states (the latter implies data is sent in bursts).

State Selection Criteria: Based on the scope of our study and on the requirements imposed by the MobiHealth users (Section II.C), we conclude that a NI state (e.g. OFF, ON-IDLE or ON-ACTIVE) depends on the following criteria:

(i) application-data delay requirement imposed by the current health condition of a patient (i.e., emergency or non-emergency),
(ii) the power$_{MBU}$ consumption while using a particular NI,
(iii) the AppRTT observed while using a particular NI.

We considered various measurements cases based on the following two parameters: application-data flow and NIs states. Each case represents a combination of MBU WLAN and GPRS NI states, while the Bluetooth interface was set to ON-ACTIVE state for intra-BAN communication. They represent possible NI states for supporting a telemonitoring application (e.g. by the MobiHealth system). These states are:

0. WLAN OFF, GPRS OFF,
1. WLAN OFF, GPRS ON-ACTIVE,
2. WLAN ON-IDLE, GPRS ON-ACTIVE,
3. WLAN ON-ACTIVE, GPRS OFF,

TABLE IV
NI'S NORMALIZED AVERAGE POWER

Case No.	Measurement case (Note: Bluetooth ON-ACTIVE for all cases)	Normalized power consumption (1/min)
0	WLAN OFF, GPRS OFF	0.00092
5	WLAN OFF, GPRS ON-IDLE	0.00487
6	WLAN ON-IDLE, GPRS OFF	0.00568
7	WLAN ON-IDLE, GPRS ON-IDLE	0.00963
1a	WLAN OFF, GPRS ON-ACTIVE (1.2-1.5 kbps)	0.00721
1b	WLAN OFF, GPRS ON-ACTIVE (5.2 kbps)	0.00874
1c	WLAN OFF, GPRS ON-ACTIVE (7.7 kbps)	0.00897
3a	WLAN ON-ACTIVE, GPRS OFF (1.2-1.5 kbps)	0.00873
3b	WLAN ON-ACTIVE, GPRS OFF (5.2 kbps)	0.00911
3c	WLAN ON-ACTIVE, GPRS OFF (NetPerf, 3.45 Mbps)	0.00982
4a	WLAN ON-ACTIVE, GPRS ON-IDLE (1.2-1.5 kbps)	0.00960
4b	WLAN ON-ACTIVE, GPRS ON-IDLE (5.2 kbps)	0.00974
4c	WLAN ON-ACTIVE, GPRS ON-IDLE (NetPerf, 3.95 Mbps)	0.00947

4. WLAN ON-ACTIVE, GPRS ON-IDLE,
5. WLAN OFF, GPRS ON-IDLE,
6. WLAN ON-IDLE, GPRS OFF,
7. WLAN ON-IDLE, GPRS ON-IDLE.

Note that theoretically, it is also possible to have the WLAN in ON-ACTIVE and GPRS in ON-ACTIVE state. However, because this case is not implemented yet in the MobiHealth system (would require substantial application changes), and also it is not supported by the operating system of the QTEK, we have not included it in our study.

Case 0 represents application "base" energy consumption, i.e. for intra-BAN communication, MBU application execution and data processing and local storage of application-data (no extra-BAN communication!). The cases 1-7 represent application "base" energy consumption increased by the energy consumption for maintaining one (or both) NI in ON-IDLE state.

Along the measurements execution we discovered that case 2 (i.e. GPRS is ON-ACTIVE and WLAN is ON-IDLE) was not possible to execute, because the Qtek 9090 is preconfigured by the OS such that, if both GPRS and WLAN are available, it will always send data over the WLAN NI rather than leaving the choice of NI to the user. The last three cases 5-7 imply continuous application execution and local data storage; i.e., no application data is being sent over a NI.

The tele-monitoring application-data flow represents the volume of application-data sent over the NI in ON-ACTIVE state. Note that our healthcare application produces 1.2-1.5 kbps of data at the NI; i.e., rate at the datalink layer (Section II.B). The calculated application-data rates are therefore:

- 1.2-1.5 kbps for continuous application execution and real-time transmission of application-data (used in emergency and non-emergency situations),
- 5.2 or 7.7 kbps corresponding to continuous application execution and delayed data sent (i.e., sending data in bursts, where 4-6 seconds of patient vital signs data represents a burst). This can be used only in non-emergency situations of a patient.

Due to the Qtek's limited processing capacity (and experienced system crashes) it was not possible to increase application-data volume beyond 7.7 kbps in case 1 and beyond 5.2 kbps in cases 3 and 4. Therefore, we obtained volumes of 1.2-1.5 kbps, 5.2 kbps and 7.7 kbps for case 1, and volumes of 1.2-1.5 kbps and 5.2 kbps for cases 3 and 4.

V. MEASUREMENTS RESULTS

A. MBU Power Consumption $power_{MBU}$

We have executed measurements for the cases described and motivated in Section IV.B. We measured the MBU's remaining battery capacity in percents, and we transformed the results into the normalized average power consumption values indicating the decrease rate of battery capacity over minutes. These normalized values facilitate comparison of the relative energy cost for WLAN and GPRS NIs in a particular device. Recall that Table II summarizes these normalized values for the Qtek device in different NIs states. We observed that in each experiment the remaining battery capacity decreases linearly over time (given the observation interval of 5 seconds). Therefore we assume that in each experiment, the normalized average power consumption value is constant.

The first 4 rows of Table IV represent cases 0 and 5-7, in which data was not sent, but locally stored at the device. Rows 1a, 3a and 4a correspond to cases of continuous application execution and real-time transmission of application-data. The other rows (1b, 1c, 3b, 3c, 4b, and 4c) correspond to cases of continuous application execution, but local data storage with delayed sending of data.

From Table IV we observe that a WLAN NI in ON-IDLE state consumes approximately the same energy as in ON-ACTIVE state (cases 4a and 7); we did not configure the Qtek device to switch to WLAN power-save mode when in ON-IDLE state. In this case, the WLAN NI continuously receives and processes all data broadcasted between a WLAN Access Point and other WLAN devices.

Moreover, to reduce device power consumption we conclude from Table II that it is always better to have only one NI in ON-IDLE or ON-ACTIVE state; i.e., use the GPRS NI and keep the WLAN OFF and vice versa.

B. Application-Data Delay (AppRTT)

Section IV.B described the executed measurement cases. We observed that AppRTT values depend on the NI(s) used and the data volume sent. Recall that Table III summarizes the results, with an emphasis on the *mean* AppRTT value. Note that these results are reported only for the telemonitoring application execution; i.e., not for the cases where we have used the NetPerf tool.

From Table V we observe that from a delay (i.e. mean AppRTT) perspective, the best option is to set a WLAN NI in ON-ACTIVE state and keep the GPRS NI in ON-IDLE state (cases 4a and 4b). In case WLAN is not available and it is necessary to use GPRS (e.g. patient is in an emergency situation), it is better to use lower data volumes (case 1a) to keep the delay low. Alternatively, it is possible to collect

TABLE V
NI'S APPRTT DELAY VALUES

AppRTT [ms] & case No.	**Mean**	stdev	min	max	med
1a. WLAN OFF, GPRS ON-ACTIVE (1.2-1.5 kbps)	3739	2005	1979	20856	3318
1b. WLAN OFF, GPRS ON-ACTIVE (5.2 kbps)	5505	2627	2767	20702	4706
1c. WLAN OFF, GPRS ON-ACTIVE (7.7 kbps)	6693	3954	2322	28220	5589
3a. WLAN ON-ACTIVE, GPRS OFF (1.2-1.5 kbps)	2753	1769	530	23807	2706
3b. WLAN ON-ACTIVE, GPRS OFF (5.2 kbps)	3513	2863	587	36819	3290
4a. WLAN ON-ACTIVE, GPRS ON-IDLE (1.2-1.5 kbps)	1806	1082	556	15756	1553
4b. WLAN ON-ACTIVE, GPRS ON-IDLE (5.2 kbps)	2211	1084	379	13609	2204

TABLE VI
PERFORMANCE OF THE BASIC NI ACTIVATION STRATEGIES

Strategy	S_{EM}(4a)	S_1(3a)	S_2(1a)
WLAN	ON-ACTIVE	ON-ACTIVE	OFF
GPRS	ON-IDLE	OFF	ON-ACTIVE
AppRTT (ms)	1806	2753	3739
power efficiency [%]	0	9	25
WWAN reachability	yes	no	yes

application data, store it locally at the mobile device and send it later over WLAN (case 4b) at the maximum volume possible (only when the patient is not in an emergency situation). It is interesting to observe that for real-time application-data transmission, GPRS has higher delay but slightly lower delay variation (i.e. stdev value) in comparison to WLAN (case 1a vs. 3a - 53 % vs. 64% of the mean value). Moreover, the delay and delay variation of WLAN when the GPRS NI is in ON-IDLE state (case 4a) are lower than those when the GPRS NI is in OFF state (case 3a). This effect may be related to the internal NI management of the mobile device used (the real reasons are unknown to us, and to the best of our knowledge similar results have not been published so far).

C. NI activation strategies

In this section, we firstly define the basic MBU NI activation strategies as sending in real-time patient vital signs data via an ON-ACTIVE NI; i.e., without application-data buffering. These strategies are denoted as S_{EM}, S_1 and S_2 and correspond to the cases 4a, 3a and 1a of Table IV. In addition, these strategies can be used in an emergency or non-emergency situation of a patient. These strategies are ordered by mean AppRTT values in Table IV, with the lowest AppRTT value (i.e. delay) for strategy S_{EM} (most recommended in emergency situations) and the highest AppRTT value for S_2. The power consumption of strategy S_{EM} is considered the reference point for comparison with other strategies.

In order to compare the average power consumption of different NI activation strategies, we assume the power consumed by strategy S_{EM} as a reference point and relative to that we define the power efficiency of a given strategy S_x as:

$$(\text{power}_{MBU}(S_{EM}) \text{ - } \text{power}_{MBU}(S_x)\ )\ /\ \text{power}_{MBU}(S_{EM}).$$

This power efficiency measure indicates the amount of power that can be saved if strategy S_x is used instead of reference strategy S_{EM}. The amount of power saving is relative to power$_{MBU}(S_{EM})$ and will be expressed in percentage. The power saving ratio becomes a positive value if strategy S_x consumes less power than S_{EM}. If strategy S_x consumes more power than strategy S_{EM}, the power saving ratio is a negative value. As such, the range of the efficiency factor defined can be any real number less than or equal to 1 theoretically. Note that the higher the resulting value, the more power efficient strategy S_x is. The last row in Table VI indicates if the strategy fulfils the requirement of a user being reachable on his/her mobile device via the WWAN-GPRS network.

For cases where higher AppRTTs are acceptable (e.g. in non-emergency situations) the MBU can adapt the application-data flow. For example, the MBU acquires and temporarily stores $n-1$ seconds, where $n > 1$, of the patient vital signs data. It sends this data and the n^{th} second data in a burst at the end of the n^{th} second to the backend-server via an activated NI. The cases in Tables II and III where data volumes reach 5.2 kbps (1b, 3b, 4b) and 7.7 kbps (1c) form the basis for our choice to consider n=4 (thus achieving 5.2 kbps) and n=6 (thus achieving 7.7 kbps).

TABLE VII
PERFORMANCE OF STRATEGIES RELATED TO APPLICATION-DATA FLOW

Strategy	S_4 (4b, $n=4$)	S_5 3b, $n=4$)	S_6 (1b, $n=4$)	S_7 (4c, $n=6$)
WLAN	alternates: ON-IDLE ↔ ON-ACTIVE	alternates: ON-IDLE ↔ ON-ACTIVE	OFF	OFF
GPRS	ON-IDLE	OFF	alternates: ON-IDLE ↔ ON-ACTIVE	alternates: ON-IDLE ↔ ON-ACTIVE
AppRTT [ms]	3000 + 2211	3000 + 3513	3000 + 5505	5000 + 6693
normalized power	0.00966	0.00654	0.00584	0.00555
power eff. [%]	-0.6	32	39	42
WWAN reachability	yes	no	yes	yes

Table VI summarizes the results of three distinctive application-data flow adaptation cases extrapolated from measurements cases: 1b, 3b, 4b and 1c. The power efficiency of a strategy is defined with respect to the S_{EM}. The following relations hold in that table: the AppRTT (i.e., application data AppRTT) is $(n-1)*1000$ plus the measured message AppRTT in [ms] and

$$\text{normalized average power} = n^{-1}((n-1)*\text{power}_{MBU}\ (\text{NI}_1\text{=ON-IDLE, NI}_2\text{=S}) + \text{power}_{MBU}(\text{NI}_1\text{=ON-ACTIVE, NI}_2\text{=S})),$$

where NI_1 represents the NI through which the data is sent, while NI_2 is being in a state S.

From Table VII we conclude that for patients in a non-emergency situation, strategies S_6 and S_7, where data is sent in burst through the GPRS NI, are more power efficient than those where data is sent through the WLAN NI; however, AppRTT is higher. The result for strategy S_4 shows that this strategy is a bit less power-efficient comparing to S_{EM}. This is due to the high power consumption of the WLAN ON-IDLE state (as we explained for Table I).

TABLE VIII
ASYMPTOTIC PERFORMANCE OF THE EXTRAPOLATED APPLICATION-DATA FLOW ADAPTATION AND NI ACTIVATION STRATEGIES

Strategy	S_8 (large n)	S_9 (large n)	S_{10} (large n)	S_{11} (large n)
WLAN alternates:	ON-IDLE ↔ ON-ACTIVE	ON-IDLE ↔ ON-ACTIVE	OFF ↔ ON-ACTIVE	OFF ↔ ON-ACTIVE
GPRS	ON-IDLE	OFF	ON-IDLE	OFF
AppRTT [ms] ≈	$n-1+C$	$n-1+C$	$n-1+C$	$n-1+C$
normalized power ≈	$0.00963 * (n-1)/n$	$0.00568 * (n-1)/n$	$0.00487 * (n-1)/n$	$0.00092 * (n-1)/n$
power eff. [%]	-0.3	41	49	90
WWAN reachability	yes	no	yes	no

For cases with larger bursts (i.e. larger n), we use the NetPerf measurements results to extrapolate the efficiency, as presented in Table V. Hereto, we estimate the maximum AppRTT by $(n-1)+C$ in seconds, where C is a constant with a slight dependency on n. This maximum AppRTT approximately represents the transmission time of n data samples and it in the order of a few seconds. Similarly, the normalized power is computed as:

$$\text{normalized average power} \approx n^{-1}((n-1) * \text{power}_{MBU}(\text{WLAN=ON-IDLE, GPRS=S}) + \text{power}_{MBU}(\text{WLAN=ON-ACTIVE, GPRS=S})),$$

where S is a given state of the GPRS NI. For large values of n, the normalized average power approaches the power$_{MBU}$ for the WLAN=ON-IDLE and GPRS=S case.

Strategies S_8 and S_9 as defined in Table VIII, disclose large difference for a WLAN NI alternating between the ON-IDLE and ON-ACTIVE state and a GPRS NI being in the ON-IDLE or OFF state. If n is large enough, one may switch the WLAN NI between OFF and ON-ACTIVE states resulting in strategies S_{10} and S_{11}. Note that for large values of n the effect of T_{on-off} and P_{on-off} on AppRTT and power efficiency, respectively, are negligible and thus they are not taken into account in Table VIII for S_{10} and S_{11} strategies.

Tables VII and VIII show that strategy S_{10} is slightly more power efficient than S_7 while it induces very high AppRTT. Only the power efficiency of strategy S_{11} is significantly higher compared to strategy S_7, but the drawback is that the mobile device is not WWAN-reachable. The results of Table VIII indicate that adapting the application-data flow (i.e. patient vital signs data sent) by sending it in large bursts (i.e. with a large n) is not power efficient enough to motivate (very) high AppRTT or being WWAN-unreachable.

VI. RELATED WORK

Related work on NI activation strategies is mainly theoretical. Moreover, it focuses mainly on applications where mobile users behave as occasional data consumers and not as data producers; e.g. in case of the MobiHealth system. For example, authors of [13]–[16] consider NI activation strategies together with methods for local or proxy-based data caching for users of email application and web-services. The work reported in [17] reduced energy consumption by introducing the NI ON-IDLE stand-by state. In this state, the mobile device is woken-up whenever there is an incoming network event (e.g. a call).

Considering the impact of applications on NI power consumption, the authors of [18] studied the WLAN NI energy consumption for different multimedia data streaming applications, like Microsoft Windows Media Player™, Real Media™and Apple Quick Time™content. They considered only a WLAN NI and downlink data streams. Similarly, but from the NI perspective, authors of [19] measured NI energy consumption of use/and alternating between a Bluetooth and WLAN NI for downloading multimedia content.

Furthermore, general research frameworks exist, in which a NI activation strategy is considered as one of multiple features. For example, the research reported in [20], [21] considered a simultaneous operation of NIs in multi-homed mobile hosts, and introduced a Basic Access Network to carry out signalling for network discovery, NI selection, inter-network handover, location updates, paging, authentication, authorization, and accounting. Authors approached the NI activation strategy objective only theoretically. Similarly, the theoretical framework proposed in [22] focuses specifically on the WLAN NI activation strategy, based on the WLAN network availability, network state (throughput, delays and reliability), as well as application QoS requirements. Their NI activation strategy assumes that the UMTS NI is always ON and available. However, they do not consider the NI energy consumption in their framework.

Authors of [23] aimed to estimate WLAN network availability and conditions without powering up a NI; it was only based on historical data. They have simulated healthcare application data for 3 leads ECG; however, they neither include Bluetooth power consumption for sensor systems nor adapted the application-data flow being sent by network (i.e. it was fixed at 5 minutes).

We would like to emphasize the contribution of our research as an extensive case study of an existing system for telemonitoring of a patient's health condition. Based on our study, we provide extensive and valuable recommendations for system users; i.e., healthcare professionals and their patients.

VII. CONCLUSIONS AND RECOMMENDATIONS

Based on our measurements, we derive conclusions and recommendations for the MobiHealth system and its COPD telemonitoring application, concerning the most efficient and effective NI activation strategies along the power and delay (as a QoS parameter) requirements. Particularly, we have observed that GPRS and WLAN NIs have complementary power and delay profiles. For GPRS, there is lower energy cost (i.e. power consumption) to maintain connectivity and lower energy cost for sending data; however, the delay is higher. On the other hand, the energy cost of WLAN can be higher, but the delay is lower. Minimal power is used in strategies where data is stored and send later it bursts (S_8-S_{11}), resulting in the highest delay (as they include long local storage time). Maximum power is used by S_{EM} (comparing to the other strategies where data is sent in real-time: S_1 and S_2), while the delay is minimal.

In an emergency situation, the WLAN ON-ACTIVE and GPRS ON-IDLE NI activation strategy should be used, as it provides the system with the lowest application data (i.e. patient vital signs) delay. However, if WLAN is not available, GPRS ON-ACTIVE and WLAN-OFF case should be used.

In a non-emergency situation we recommend the use of the WLAN ON-ACTIVE and GPRS ON-IDLE strategy if a user needs to be reachable. In this situation, data can be sent in bursts and power usage needs to be optimized. The recommended burst size corresponds to 4 seconds of patient vital signs data. However, if WLAN is not available, GPRS should be used with WLAN OFF and a recommended burst size corresponding to 6 seconds of patient vital signs data. Bursts size corresponding to larger number of seconds of patient vital signs data is not power efficient enough to motivate (very) high delay AppRTT or being unreachable for a voice call.

The measurement methods and results reported in this paper are useful when considering a broader context, e.g. as direct contributions to the design process of adaptive-application protocols. The rules and guidelines obtained may be used in a closed loop control mechanism vertical handovers for multi-homed mobile devices as, for instance, proposed and investigated in [24], [25]. With monitoring functionality built into the mobile device and adequate decision strategies, network access can be optimized according to preferred performance objectives.

The results presented in this paper can be generalized over a class of devices having the same technical specifications as Qtek 9090. The measurements-based approach presented in the paper, can be repeated for any other device used as the MobiHealth's MBU, any other location-timeframe, any other network (e.g. UMTS).

As a future work, we recommend research on more elaborated NI activation strategy methods. Possibilities are to include delay-trends (as presented in the Section III.C) and/or include multiple periodic application-data flows with different delay requirements per flow. We believe that a NI activation strategy must include monetary cost of network usage and network security facilities that may be required by MobiHealth users. Finally, we plan to extend our study of power and delay based application-data flow adaptation from a stationary user location to different mobility levels, where data is sent over different available WWAN networks (e.g. GPRS, UMTS, HSxPA) at a given user (geographical) location and time of transmission.

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