HWL – A High Performance Wireless Sensor Research Network

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***Abstract*—Current Wireless Sensor Networks (WSN) consist of low powered energy efficient nodes with short range radios and limited computation capabilities. Sensing applications with multiple sensors, high sample rates, and large spatial coverage are not realizable with conventional WSNs.**

We propose High Performance WSNs (HP-WSN) with an 802.11n based physical layer and opportunistic routing to overcome the limitations of existing WSNs. We present a research test-bed for such HP-WSNs. As an intermediate step towards actual HP-WSNs, our test-bed (HWL) collects raw data into a centralized data store to provide an experiment friendly environment. The collected raw data includes sensor data (to develop new sensing applications) and data about network and system operation (to develop the sensor network).

We provide an example HP-WSN application, derive research objectives for the development of HP-WSNs, provide a test-bed architecture and present evaluation results on network and data storage performance to show the principle feasibility of HP-WSNs.

***Index Terms*—Wireless Sensor Networks, IEEE 802.11n, Opportunistic Routing, Research Testbed**

I. Introduction

Wireless sensor networks (WSNs) [1] are battery powered wireless multi-hop networks, where each node is equipped with multiple sensors. WSNs allow to sense the environment without any existing infrastructure. Typical WSNs use low powered and energy-efficient hardware with short-range radio communication typically based on Wireless Personal Area Networks (WPAN), e.g. IEEE 802.15.4 (tmote sky[1]). As main characteristic these WSNs use short duty cycles and long periods of inactivity to preserve batteries. Thus, WSNs are tailored for measurements at low sensor sample rates or over short periods of time. Due to high energy consumption of radio communication, WSNs typically record data locally and communicate only aggregated data of small size (Fig. 1, left).

Typically WSNs are used to measure a single physical variable. Applications include measurement of temperature, sensing the presence or absence of objects, the monitoring the structural health of buildings via vibrations and natural frequencies (Structural Health Monitoring (SHM) [2]), or sensing the acoustic stress by measuring noise levels [3].

WNS applications are limited by computation and networking capabilities of WSNs. Applications such as SHM with higher sample rates at multiple channels, recording of audio (e.g. speech in contrast to just noise levels), measuring patterns such as bitmaps created by video cameras [4], or measuring multiple properties at once (e.g. detecting correlation between temperature and natural frequencies in concrete) require a different kind of WSN. Such applications produce different types of data in large amounts in a short period of time.

[1] http://www.snm.ethz.ch/pub/uploads/Projects/tmote_sky_datasheet.pdf

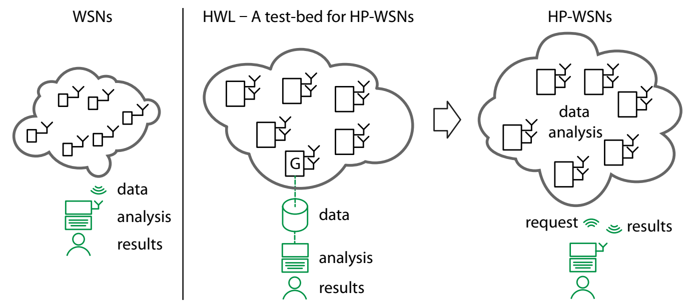

Fig. 1. The HWL test-bed enables the development and analysis of applications for HP-WSN.

We propose *High Performance WSNs* (HP-WSN) based on Wireless Local Area Network (W-LAN), e.g. IEEE 802.11, a larger physical size, higher battery weight, or even cable based power supply. Compared to managed wired networks ad-hoc HP-WSNs still allow a fast and cost effective way to install a communication and sensing infrastructure in a previously unknown and changing environment. Beyond sensing, HP-WSNs provide enough capabilities to run data analysis within the network (Fig. 1, right).

In this paper, we present the *Humboldt Wireless Lab* (HWL), a research test-bed for the development of HP-WSNs and their applications. HWL consist of WLAN nodes based on the 802.11n standard and offers research opportunities and potential higher data rates based on 802.11n features such as MIMO or opportunistic routing. HWL operates as intermediate step towards the development of actual HP-WSNs (Fig. 1, center). During research, operational parameters of networking and OS layers (such as network statistics, CPU-, memory-, and power-consumption, etc.) complement sensor data. During this phase, all raw data is retrieved from the network and is stored in a centralized data store. HWL uses technology from the software modeling world for data representation and analysis, thus providing an experiment friendly research environment. After validating applications in this environment

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the application can be reworked for distributed environments and to run in production HP-WNSs without centralized data store (Fig. 1 right).

The paper is organized as follows. In the next section, we define a set of requirements for HP-WSNs. We describe HWL and its architecture in section III. The following section evaluations HWL's data centralization and real time storage capabilities. At the end, we present related work and our conclusions. We published a longer version of this paper as techreport [5].

II. Requirements

First, we describe requirements for network and data storage performance based on expected data rates for HP-WSNs. Secondly, we explain the necessity for further scalability and describe scalability implied requirements.

A. Network Capacity

To determine the required network capacity we take a look at the required data rate on application layer. In Fig. 2 we show the data rate for 4 typical sensing applications [6]: (A) barometer pressure (28 Hz sample rate): 900bit/s, (B) structural health monitoring [2] (with accelerometers at 100 Hz, 3 channels): 9.6kbit/s , (C) audio, low quality: 45kbit/s, (D) video, low quality: 256kbit/s. Note that data from all nodes has to go though one (or few) gateway nodes. We can see that even for a low sensor data rate and small network size the total data rate becomes high enough for wide-band wireless technology; e.g. a SHM application (B) and a network size of 100 nodes results in a total data rate of around 1 Mbps.

Notice, that to achieve a given data rate on the application layer the required data rate on the MAC/PHY must be much higher due to multi-hop forwarding, serialization of transmissions within the wireless collision domain, MAC layer overhead, etc.

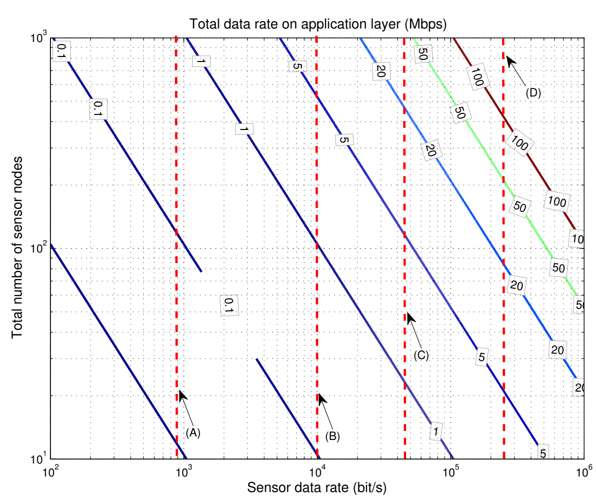

Fig. 2. Data rate on application layer (Mbps) depends on the number of sensor nodes and the sensor data rate.

B. Storage Speed and Capacity

Even if the network capacity is sufficient to transfer the raw sensor values, the data storage system has to store the data at the same rate. During analysis, one wants to read specific dataset for data analysis as fast as possible. Traditional approaches based on writing simple log files are slow to read selectively and relational databases (RDBMS) are unable to store data fast enough (see section IV). Therefore we propose to use No SQL databases (refer to section III-D).

C. Scalability

Even with enhanced networking and database storage performance, increasing requirements for network capacity and storage speed will eventually require a scalable HP-WSN architecture. Data sinks (aka gateway nodes) are the bottlenecks in a HP-WSN, since they have to forward the data of all nodes. Therefore the networking capacity towards data sinks limits the rate at which sensing data can be generated in the network. Furthermore, the rate at which data can be stored in a single database running on a single computer is limited. Therefore, also the data storage system can also be the bottleneck for a HP-WSN network.

There are the two dimensions that can be used to scale a HP-WSN. First, one can increase the number of data sinks / network gateways. Second, distributed databases allow distributing the load over multiple computers. This requires the possibility of multiple gateway nodes and a easily distributable data store.

III. Proposed Architecture

A. Wireless Mesh Node

We picked the Netgear WNDR3700[2] as 802.11n based mesh node. It is an off-the-shelf wireless router equipped with two 802.11n compliant radios. The WNDR3700 has an Atheros (AR7161, rev 2) MIPS CPU, running at 680 MHz, and 64 MB of RAM and 16 MB of flash memory. It also has a Gigabit Ethernet adapter and an USB2 interface.

The WNDR3700 has two 802.11n radios; each with 4 internal metamaterial antennas from Rayspan[3]. The first radio is dual-band (Atheros AR9220) allowing operating in the 2.4 as well as 5 GHz band, whereas the second radio can only be operated in the 2.4 GHz band (Atheros AR9223). Both radios support 2x2 SM-MIMO (2 spatial streams), channel bonding (40 MHz channel) as well as the possibility to use short guard OFDM interval (SGI). The maximum data rate at the PHY layer is 300 Mbps. Both wifi chips also support STBC, thus achieving a transmit diversity gain. The optional transmit beamforming is not supported.

The linux-wireless project [7] develops the ath9k, an open source driver for Atheros 802.11n chipsets, which allows to develop customized 802.11 MAC protocols. Furthermore, the

[2]http://www.netgear.com/home/products/wirelessrouters/high-performance/WNDR3700.aspx

[3]see http://www.commnexus.org/assets/011/9474.pdf

PHY parameters can also be adapted. The widely used Open-Wrt[4] functions as operating system. Refer to our technical report [8] for further details.

Routing protocols are implemented with the Click Router API [9]. In addition to existing state-of-the-art single-path routing protocols like link state aware *Dynamic Source Routing* (DSR) and *Ad hoc On-Demand Distance Vector* (AODV) routing is also possible to implement and evaluate opportunistic routing protocols like ExOR [10] and MORE [11]. For the later one the processing speed of our mesh nodes (680 MHz) is sufficient to support network coding.

The procurement cost for a single mesh node is below 100 $ which allows to build large-scale mesh networks at reasonable costs.

B. Sensors

For our specific SHM applications the nodes are equipped with a motion sensor board that delivers acceleration values (accelerometer). The board comprises of two STMicroelectronics LIS2l02AL 2-axis linear accelerometers. The combined sensors measure linear acceleration along three orthogonal spatial axes (X,Y,Z). The A/D-converter samples with a density of 21 bits per axis value and sample rates from 100 Hz up to 2 kHz. The sensor board measures between +/-2 g and has an output noise of 0.2 mg. Each sensor reading is timestamped (with GPS time). This setup produces data streams from 14 kbit/s up to 280 kbit/s.

C. ClickWatch

Routing and higher layer protocols and applications are realized within MIT's Click Modular Router API [9]. Lower level components like MAC, network drivers, and sensors expose themselves via Click proxy elements into the Click world. Thus all software components on a node are either directly or indirectly represented as Click elements.

ClickWatch [12] allows to remotely access Click runtimes, retrieve data, and create a centralized record of all the node's data. Furthermore, ClickWatch creates a homogenous typed representation of the received data, it can record data into a database (see section III-D), and it provides model driven API's for accessing recorded or live data in a type-safe manner. ClickWatch's unique feature is the ability to identify and respect the inherit (even if implicit) structure of received data. All data is represented as a tree structure. This structured data approach serves two goals: (1) data is easier understood by human users, since the data can be visually presented as trees; (2) data analysis becomes more efficient, since you can handle pieces of data type-safe and data structure propagates into a more structured analysis. ClickWatch is discussed in more detail here [12].

D. No SQL database

Motivated by the constant high data rates over arbitrary stretches of time, a database has to store large amounts of data a quickly. Data analysis further demands proper data store granularity to allow fast access of distinct pieces of data.

For those reasons, we neglect the use of both common approaches: log-files and SQL-databases. Log-files can be stored fast, but provide no means of indexing (other than timestamps). SQL-databases allow queries and indexes at arbitrary granularity, but (at economically reasonable prices) don't store data fast enough or scale well. Fortunately, no SQL databases (especially key-value stores) provide a solution. Key-value stores only consist of one (big) table used to store key-value pairs. Such tables are easily distributed and scale arbitrarily. The weakness of the approach is the limited granularity.

How much granularity is needed? Click handlers determine the granularity. They are read at configurable intervals and therefore allow us to determine the size of data store entries. Thus enabling us to use as few as possible samples per entry as the data store write performance and required data rate allow. This issue is discussed in more detail in the evaluation section IV.

IV. Evaluation

In this paper, we present the evaluation of HWL towards one aspect: the realtime storage of live sensor data. Other aspects are covered in the paper's long version [5].

We measured three data store solutions: (1) simple log-files, (2) MySQL (5.0.8) as relational database, (3) Apache HBase (0.90.3) as a No-SQL database. All measures were conducted on a single computer with an Intel Xeon E31245 3.3 GHz 8 core CPU, 8 GB RAM, Ubuntu Linux 11.

We conducted two experiments, one with artificial data and one with actual HWL sample data (covered in [5]). The first experiment determines the different data store capabilities with respect to data rate and used record size. The data rate determines the amount of data a WSN produces per second, the

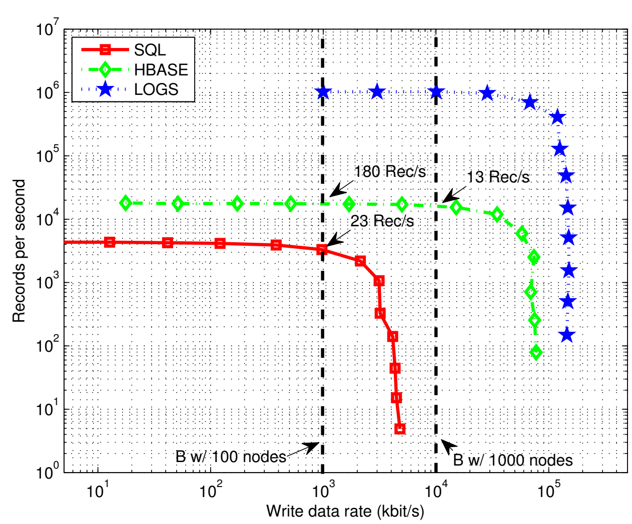

Fig. 3. Data storage performance with artificial data.

[4]http://www.openwrt.org/

record size determines how granular data is stored separately and therefore can be accessed separately. Fig. 3 shows the write performance of the different data store solutions.

The write performance chart plots the maximum possible number of records per seconds that can be used with a given data rate. The more records per seconds, we can use, the more granular data can be stored and accessed. For both data rate and record rate, we have to remember that one data store is responsible for multiple node or whole WSNs.

For a 100 node WSN (e.g. with seismic sensors), where each node produces sensor date with 9,6 kBit/s, the whole WSN produces 960 kBit/s. The MySQL database can store 2,400 records per second. This means for each node the database can store 24 record per second. With 100 Hz sample rate, 5 samples have to be put into each record. This is the granularity that we can access data during analysis. HBase can store roughly 180 records per second; each sample can get its own record. For the same data in a 1,000 node network, MySQL cannot store the data anymore no matter how big the records are and HBase can still store 13 records per second, thus 10 samples per record granularity.

V. Related Work

Existing *Wireless Sensor Networks* (WSN) [1] are based on energy efficient short-range narrow-band radio communication like the tmote sky[5]. Most well known test-beds are MoteLab [13] as well as the TWIST test-bed [14]. The MoteLab is deployed at the Harvard University and consists of more than 190 TMote Sky sensor nodes whereas TKN Wireless Indoor Sensor network Test-bed (TWIST) consists of 102 TmoteSky and 102 eyesIFX nodes and is located at the TU Berlin campus.

There is a large number of *Wireless Mesh Network* (WMN) test-beds used in the research community based on the outdated 802.11a/b/g standard. WMNs are mostly seen as community access networks. Most well known are the MIT Roofnet [15] and Microsoft Research test-bed [16]. The Roofnet at MIT CSAIL is one of the first experimental 802.11b/g WMN test-beds, which provides broadband Internet access to campus users. CitySense [17] is an open test-bed for researchers in a large-scale urban setting.

VI. Conclusion

Sensing applications are limited by the capabilities of conventional WSNs. We proposed high performance wireless sensor networks (HP-WSNs) based on an advanced PHY/MAC layer introduced by 802.11n and novel routing schemes, specifically opportunistic routing. We build a test-bed for HP-WSNs and conducted measurements to prove the feasibility of HP-WSNs.

From the ongoing research and our own experiences discussed in this paper, we conclude that advanced networking techniques on PHY and MAC layer (such as MIMO) and routing layer (such as opportunistic routing) allow data rates that make new sensing applications (e.g. for audio and video data) reasonable. But we also know that combining different new approaches on PHY, MAC and routing layer not necessarily produce the combined advantages and that methods and protocols have to be reevaluated in the context of HP-WNSs as future work.

For the purpose of research, we proposed that raw sensor data is centralized of data analysis to provide an experiment friendly environment in the development phase of WNS applications. The presented measurements indicate that NoSQL databases and their key-value approach to data storage are more suitable for sensor data than the (in the WNS field) predominant log-file approach or traditional relational databases.

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