A Study of Long-Term WSN Deployment for Environmental Monitoring

Miguel Navarro[*], Tyler W. Davis[†], Yao Liang[*], and Xu Liang[†]
[*]Department of Computer Science, Indiana University – Purdue University Indianapolis
[†]Department of Civil and Environmental Engineering, University of Pittsburgh
mignavar@cs.iupui.edu, twd2@pitt.edu, yliang@cs.iupui.edu, xuliang@pitt.edu

***Abstract*—In this paper, the ASWP testbed, a long-term wireless sensor network (WSN) deployment for environmental monitoring, is presented. This testbed implements a periodic sampling application for external sensors exposed to a forested outdoor environment in western Pennsylvania, USA. It has been running for the past two years using TinyOS-based WSN platforms and the commercially available routing software XMesh. ASWP's performance is analyzed in detail for the period of August 2011 to August 2012, focusing on packet duplication, packet loss, and network maintenance. The results indicate that the critical impact due to the outdoor environment and node physical failures significantly reduced the network yield when long-term periods were considered. In particular, it is found that an over-used routing path across the network was responsible for most of the packet retransmissions and drops in ASWP. This work intends to provide a reference point for WSN research and development targeted towards outdoor WSNs for long-term deployments.**

I. Introduction

During the past few years, the development of commercial and research platforms for wireless sensor networks (WSNs) has prompted an increasing interest in a broad range of new scientific research and applications. WSN technologies provide high resolution spatial and temporal data at a declining cost per area, thus making them an affordable and practical option for many researchers [1]. Additionally, it is very common that WSNs are deployed for various domains, where scientists and engineers require solutions in which they do not have to directly handle the complexity of these systems. As a result, off-the-shelf commercial solutions are usually preferred if timely interdisciplinary collaborations with WSN researchers are not available.

The adoption of WSNs represents new challenges for end-users who require high-quality data collections and optimal network behavior, particularly for WSNs deployed in challenging outdoor environments. Indeed, simulation and laboratory methods are unable to capture the complexity of outdoor environments (e.g., forests, oceans, mountains, or glaciers), which affects the WSN functionalities. Consequently, real-world experimental deployments are required to study and analyze these harsh conditions.

This paper presents the study of an outdoor WSN testbed deployment that has been operating continuously for more than two years in Pennsylvania, USA. This experiment, named ASWP testbed, is deployed in a forested nature reserve at the Audubon Society of Western Pennsylvania (ASWP), where it faces a more adverse environment and operation conditions compared to many open-area experiments. The location includes multiple obstacles (e.g., extreme weather, wild life, and flora), which limit node locations, presenting a great challenge for the WSN performance.

WSNs deployed for environmental monitoring often require collaborative efforts with customized research hardware and software, which may be an unfeasible option for many research and application projects due to development time and budget constraints. This study is centered on the deployment of a long-term WSN testbed that uses TinyOS-based platforms and a commercially available routing and application software (XMesh), for an evaluation purpose under adverse, but realistic conditions. Furthermore, this work provides a useful reference point that can be used as a performance baseline for researchers in their future WSN deployments and evaluations.

This WSN study constitutes, to our knowledge, the first comprehensive evaluation of a commercially available WSN platform for environmental monitoring research and during a long operational period (i.e., more than two years). The main objectives of this work are to analyze the network performance and the quality of the collected data to characterize the WSN maintenance with its impact in the network behavior, and to validate the testbed deployment to determine if the WSN performance is adequate for similar research needs. The rest of this paper is organized as follows. Section 2 reviews related WSN experiments. Section 3 describes the testbed deployment. Section 4 presents the network analysis and key results. Finally, Section 5 gives the conclusions and outlines future work.

II. Related Work

WSN deployments can be classified into two major categories depending on their applications: periodic sampling/sensing and object detection/tracking. These two categories have different requirements and thus they are tested in different scenarios. On one side, periodic sensing applications target extensive operational time periods and therefore require low-power consumption due to limited energy resources. The second category aims for shorter

978-1-4577-1348-4/13/$31.00

TABLE 1: CHARACTERISTICS OF RELATED WSN DEPLOYMENTS

	Deployment time	Size	Environment	Platform	Application
SNE [5]	123 days	43 nodes	Outdoors	Mica	Periodic sensing
TRIO [3]	4 months	557 nodes	Outdoors – open area	Trio Mote	Tracking / detection
GDI [6]	4 months	98 + 49 nodes	Outdoors	Mica2Dot	Periodic sensing
SensorScope [4]	2 months	< 100 (16) nodes	Outdoors – glacier	TinyNode	Periodic sensing
Redwoods [7]	44 days	30 nodes	Outdoors – tree	Mica2Dot	Periodic sensing
GreenOrbs [9]	29 days (~year)	330 nodes	Outdoors – forest	TelosB	Periodic sensing
ExScal [2]	15 days	1200 nodes	Outdoors – open area	Mica2(eXtreme Scale)	Tracking / detection
VigilNet [8]	~ 5days	70 nodes	Outdoors – open area	Mica2	Tracking / detection
ESS [10]	~ few days	40 nodes	Outdoors	PC104 nodes	Periodic sensing

operational time periods, low latency, and always-on configurations [2]. ASWP testbed belongs to the first category, implementing a periodic sensing application.

Table 1 summarizes the most representative WSN deployments reported in the past few years, specifying their deployment time, network size, deployment environment, platform, and main application category. The largest deployment durations are in the order of months and they were achieved mainly by testbeds with renewable energy supplies (i.e., solar panels), which allow them to recharge their node batteries. Trio [3], SensorScope [4], and SNE [5] are deployments with these characteristics. There are other specific experiments based on the motes' battery, such as GDI [6], Redwoods [7], ExScal [2], and VigilNet [8], with deployment durations of days or months.

As mentioned above, not all outdoor testbeds undergo the same kind of environmental conditions as those found in a forested area, where several factors aggressively affect wireless communications and make the motes more susceptible to physical failures. GreenOrbs [9] is one of the few testbeds that presents similar environmental conditions to the ASWP testbed. However, their reported continuous operations are still in an order of days to a few months. Several other WSN deployments have been reported for demonstration purposes, also limiting their deployment durations to the order of days [10] [11] [12].

III. TESTBED DESCRIPTION

The testbed is deployed at the ASWP's Beechwood Farms Nature Reserve (BFNR), which is located in Fox Chapel in northern Allegheny County, Pennsylvania, USA. The BFNR is 134 acres of protected land, which is owned by the Western Pennsylvania Conservancy. The reserve facilitated power and internet needs for the WSN gateway and it had an accessible wooded area where nodes could be installed. The reserve attracts mostly nature enthusiasts and its hiking trails are closed from dusk to dawn, so the equipment was relatively well protected from human interference.

The purpose of this deployment was to explore the status and trends of soil moisture and transpiration within the local watershed. The data are collected for calibration and validation of physically based hydrologic and land surface models. These models require high resolution ground-based measurements which can be provided by WSN deployments.

A. Deployment

At the time the project started, the main competitors for WSN technology were Crossbow's MICAz [13] and MoteIV's Tmote Sky [14] motes. Crossbow was selected for this project because they had reliable and effective technical support, even though their products were slightly more expensive. The MICAz MPR2400 radio and processor board was used for the base station and wireless motes. The MDA300 data acquisition board [15] was selected because it provides onboard sensors and external connections. The onboard temperature and humidity sensors on the MDA300 allow for monitoring a mote's environment (e.g., checking for overheating and wet conditions) and they were used on all the wireless motes. In addition, the MDA300 data acquisition boards provide seven analog sensor inputs used to connect the external environmental sensors.

Based on the desired area for sensor measurements, the location was divided into three sites. Site 1 corresponds to the area next to the Nature Center, where the WSN gateway and the base station are located. The purpose of this site is to relay the information from the motes to the base station. Sites 2 and 3, which were designated as areas to conduct field sensor measurements, are located in the forested hill-sloped region of the reserve. The three sites, including the sensor locations, are presented in Figure 1.

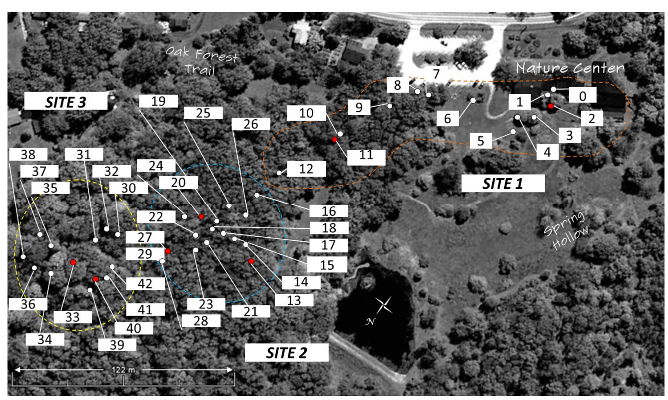

Figure 1. A map of the study area indicating the relative locations of the base station and the nodes in sites 1, 2 and 3. The node locations are representative to the network configuration in December 2012.

The testbed deployment began in April 2010 and it was divided into phases to test network connections and to progressively deploy the sensor nodes in different configurations. Figure 2 illustrates some of the sensor node configurations used at ASWP. In August 2010 the network consisted of 40 nodes and since then it has had a few modifications. The most significant occurred in March 2012 when different nodes were relocated and the network size was increased to 42 nodes. Both of these additional nodes were relays (e.g., motes without external sensors) positioned near the interface of sites 1 and 2. The additional relay nodes and select nodes in the network were replaced with new Iris motes [16] from MEMSIC Inc. (previously Crossbow Inc.). These motes are more energy efficient and have a stronger antenna power compared to regular MICAz motes.

Figure 2. Sensor nodes configurations: Relay nodes on the ground (left), hanging relay nodes (center) and nodes with external sensors (right).

B. Gateway and Data Management

After selecting Crossbow for the WSN technology, their Stargate NetBridge served as the WSN gateway, which is a modified NSLU2 device. It remained in operation until July 2011 when it had to be replaced with a new Linux-based gateway platform. The need to create a new gateway platform stemmed from the shortcomings of the Stargate NetBridge gateway [17] [18].

During the time that the first gateway was in use, remote connectivity was made using a simple web service manager. The Apache AXIS2/C web service was chosen because it was compatible with the ARM architecture and had low computational power and memory requirements. The gateway operated as the server while a computer located at the University of Pittsburgh, with the client software installed, requested daily data for downloading. Following the move to the Linux gateway, Dropbox file synchronization and backup service was used in place of AXIS2/C. Dropbox provided a more sophisticated and user-friendly alternative. In addition, the developed web-based WSN management system, INDAMS (Integrated Network and Data Management System for Heterogeneous WSNs), was incorporated into the gateway for real-time data monitoring, network status and connectivity information [19].

IV. Network Analysis

The WSN operates using XMesh's multi-hop routing protocol [20], which offers three basic types of application packets: sensor data packets, node health packets and neighbor health packets. Sensor data packets contain the readings from the MDA300 acquisition board; node health packets contain node level accumulated statistics (i.e., node health packets generated, total packets generated, forwarded packets, retransmissions, path cost, link quality); and neighbor health packets are used to report the cost and link information from up to five neighbor nodes. Different sampling periods were used in the testbed depending on the packet type: 15 minutes for sensor data packets and 20 minutes for health packets. Route information packets had a sampling period of 128 seconds; however, node packets in the following analysis only refer to application-level packets.

Important aspects of WSN deployments, in addition to the objective of the main application, are the mechanisms that allow evaluating network performance and informing end-users about the network status at any time. For this purpose, a methodology for network analysis is examined based on two of the main concerns of end users for WSN deployments: data quality and maintenance costs.

The quality of collected data is often evaluated based on statistical methods that consider the amount of samples available and the precision of the instrument used to measure them. When WSNs are used as data gathering mechanisms, samples collected by mote sensors are forwarded as packets towards the base station. Major factors that affect the quality of the data include packet duplication and packet losses, which should be examined before any domain-specific analysis. Most protocol stacks available for WSNs, including XMesh, provide different kinds of mechanisms to address, though partially, these problems.

The initial dataset contained more than 900,000 packets collected between August 2011 and August 2012. This time period is divided into two sub-periods to consider the different network sizes: period 1 (P1) from August 2011 to February 2012 (40 nodes), and period 2 (P2) from March 2012 to August 2012 (42 nodes). In addition, 35 consecutive days of

TABLE 2: NETWORK LEVEL PERFORMANCE

Period	Node Health Duplicates	Sensor Data Duplicates	Neighbor Data Duplicates	Network Yield	Packet Success Ratio	Node Packets Received (Avg. per day)	Node Packets Generated (Avg. per day)
P1: 08/2012 – 02/2012	4.10%	3.82%	3.65%	35.17%	49.09%	2,391	6,798
35 days P1	3.74%	3.43%	3.71%	61.04%	53.92%	3,861	6,250
P2: 03/2012 – 08/2012	3.16%	3.01%	3.08%	36.01%	46.08%	3,194	8,869
35 days P2	2.30%	2.25%	2.41%	42.16%	45.33%	3,577	8,484

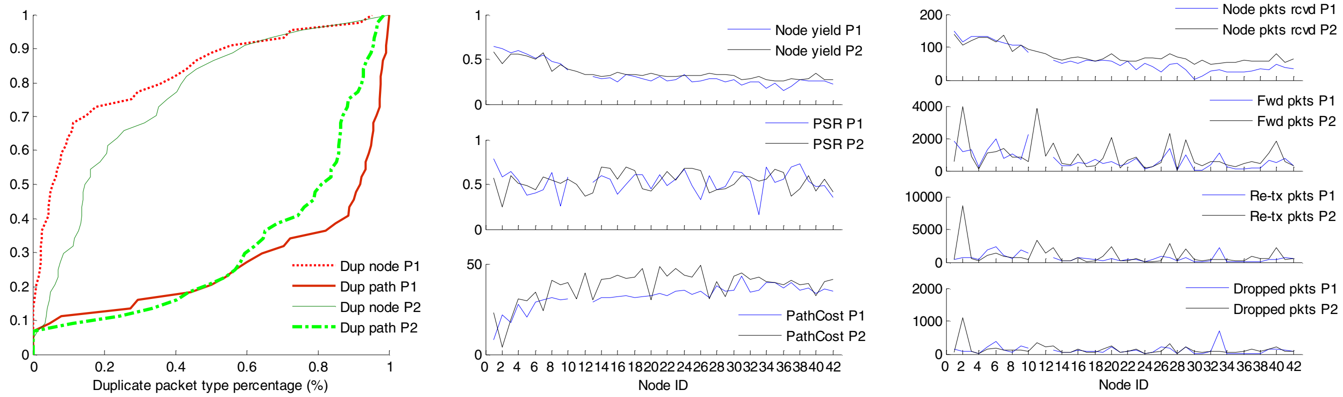

Figure 3. (a) CDF of each type of duplicate packet: duplicates at the origin node and duplicates along the path. (b) Node yield, PSR, and XMesh path cost in average values per day per node. (c) Received pkts, forwarded pkts, retransmissions, dropped pkts in average values per day per node.

operation were selected from each sub-period to compare results between short-term and long-term operations.

A. Network Level Results

Initially, network level results present a general overview of the network performance as shown in Table 2. It was found that around 3% to 4% of the packets received corresponded to undetected duplicated packets, with small percentage differences between packet types. In addition, there were up to 7 duplicates for the same original packet, which corresponds to the maximum number of retransmissions configured in the testbed. These results provide an initial insight, indicating that the network may be under continuous packet retransmissions.

The network yield and the packet success rate (PSR), as defined in (1), support this observation given that only 35% to 61% of the packets generated in the network safely arrive to the base station, and that the probability of a successful transmission in most cases is below 50%.

$$yield = \frac{received_{pkts}}{generated_{pkts}}\ ; \qquad PSR = \frac{gen_{pkts}+fwd_{pkts}-drop_{pkts}}{gen_{pkts}+fwd_{pkts}+reTx_{pkts}} \tag{1}$$

It is important to emphasize the significant difference in the network yield when short periods are considered as seen in Table 2. Knowing that there is only a minor change in the PSR, the lower yield in long-term experiments is mainly a consequence of battery depletions, eventual hardware failures, and the capacity of the routing protocol to react and adapt to those events. An additional observation with respect to the second period is that it operates under higher traffic compared to the first period due to the additional and more efficient node replacements. Even though the results obtained are lower than expected, they are still comparable to other reported results: GDI [6] median node data yield of 58%, Redwoods [7] median data yield of 40%, and GreenOrbs [9] reports network yields from 10% to more than 60% in different scenarios.

B. Node Level Results

Results at the node level are presented to further analyze the network performance. Based on the node health information, it is possible to determine if a duplicate packet was created at the source node or if it was duplicated in some intermediate node along the path towards the base station. Figure 3a depicts the Cumulative Distribution Function (CDF) for node health packets duplicated in the source node and along the path. It indicates that a median of 95% duplicate packets were created along the path and only the remaining 5% were duplicated at the origin node, during the first time period. A similar tendency is observed for the second period, in which a median of 85% of the duplicates were created along the path. These results suggest that only a few nodes in the network are originating most duplicate packets and potential bottlenecks.

To validate this observation, Figure 3b and Figure 3c present the node-level indicators and statistics in average values per node per day. Higher node IDs indicate nodes located farther from the base station. In the figures, it is possible to see that there are significant differences in node yield and the number of packets received for nodes located farther from the base station, and these differences are consistent when comparing both time periods. Furthermore, the figures illustrate that most forwarded packets, as well as retransmissions and dropped packets can be associated to a small group on nodes across the network (i.e., nodes 2, 11, 20, 27, 29, and 40). This group of nodes constitutes a highly used path, which at the same time may produce a bottleneck effect in the WSN.

During the second period there is more evident bottleneck problem for nodes located closer to the base station, as they are responsible for most retransmissions and packet drops. Even though site 1 (see Figure 1) has some space limitations, the topology offers alternatives, confirmed by the connectivity information, to route packets across. These alternatives are not exploited and balanced by the routing protocol; therefore, XMesh was not able to identify and correct this problem, as evidenced in Figure 3b, where it continues assigning the lowest path cost to those highly used and bottleneck nodes.

C. Network Maintenance

To provide an insight into the impact of network maintenance on network performance, the number of confirmed manual restarts was computed for each node. Node manual restarts considered may be the result of battery replacements, node replacements, or node relocations. Node

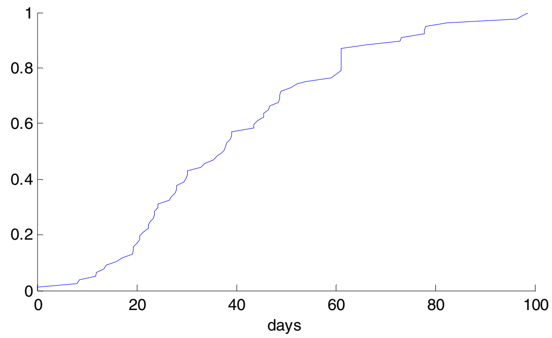

Figure 4. CDF of the time between manual restarts per node during the complete time period (August 2011 – August 2012)

restarts caused by malfunctions are excluded and they were identified as multiple node restarts within a few minutes or hours.

Using this information, the time between node restarts can be estimated. In Figure 4, these results are presented as the CDF of the time between manual restarts per node. It can be seen that in less than 10 days, 4% of the nodes (i.e., one or two nodes) may require attention. On average, nodes require attention after 38 days, although several nodes lasted up to 100 days without any attention.

V. CONCLUSIONS

This study presents an analysis of the ASWP WSN testbed[1]. This is a two-year study of a WSN operating in an outdoor environment using TinyOS based WSN platforms and commercially available routing software XMesh, for the purpose of environmental monitoring.

In the context of environmental monitoring applications, accurate results can be produced from sub-daily data samples; therefore ASWP testbed succeeds in providing the required data, in addition to the benefit from a higher spatial resolution allowed by WSNs, compared to other traditional data collection approaches (i.e., data loggers). However, from the network perspective, the overall performance can still be significantly improved, increasing the nodes battery life, reducing the network maintenance costs, and allowing deployments for new applications with more restrictive requirements.

From network-level and node-level results it is possible to identify highly used nodes by their number of forwarded packets and retransmissions. An unexpected result was obtained when several of these highly used nodes presented a lower path cost compared to their neighbors, indicating that the routing protocol XMesh was not able to identify and correct this problem.

Future work includes: (1) implementing this network analysis into INDAMS online management system [19] to generate updated and accurate indicators of the network performance in near real time, which helps to optimize the network operations and maintenance; and (2) improving the protocol stack to address the main challenges identified.

[1] The data collected from this and other testbeds is available at the website: http://sensornet.cs.iupui.edu

VI. ACKNOWLEDGEMENTS

This work was supported by NSF under CNS-0758372 and CNS-0721474 to IUPUI and the University of Pittsburgh, respectively.

REFERENCES

[1] I. F. Akyildiz, W. Su, Y. Sankarasubramaniam and E. Cayirci, "Wireless sensor networks: a survey," *Computer Networks,* pp. 393-422, 2002.

[2] S. Bapat, V. Kulathumani and A. Arora, "Analyzing the Yield of ExScal, a Large-Scale Wireless Sensor Network Experiment," in *IEEE ICNP*, 2005.

[3] P. Dutta, J. Hui, J. Jeong, S. Kim, C. Sharp, J. Taneja, G. Tolle, K. Whitehouse and D. Culler, "Trio: Enabling Sustainable and Scalable Outdoor Wireless Sensor Network Deployments," in *ACM IPSN*, 2006.

[4] G. Barrenetxea, F. Ingelrest, G. Schaefer, M. Vetterli, O. Couach and M. Parlange, "SensorScope: Out-of-the-Box Environmental Monitoring," in *ACM IPSN*, 2008.

[5] R. Szewczyk, J. Polastre, A. Mainwaring and D. Culler, "Lessons from a sensor network expedition," *Lecture Notes in Computer Science,* pp. 307-322, 2004.

[6] R. Szewczyk, A. Mainwaring, J. Polastre, J. Anderson and D. Culler, "An analysis of a large scale habitat monitoring application," in *ACM SenSys*, 2004.

[7] G. Tolle, J. Polastre, R. Szewczyk, D. Culler, K. Turner, S. Tu, S. Burgess, T. Dawson, P. Buonadonna, D. Gay and W. Hong, "A macroscope in the redwoods," in *ACM SenSys*, 2005.

[8] T. He, S. Krishnamurthy, L. Luo, T. Yan, L. Gu, R. Stoleru, G. Zhou, Q. Cao, P. Vicaire, J. Stankovic, T. Abdelzaher, J. Hui and B. Krogh, "Vigilnet: An integrated sensor network system for energy-efficient surveillance," *ACM Transactions on Sensor Networks,* 2005.

[9] Y. Liu, M. He, M. Li, J. Wang, K. Liu, W. Dong, Z. Yang, M. Xi and J. Zhao, "Does Wireless Sensor Network Scale? A Measurement Study on GreenOrbs," in *IEEE INFOCOM*, 2011.

[10] A. Cerpa, J. Elson, D. Estrin, L. Girod, M. Hamilton and J. Zhao, "Habitat Monitoring: Application Driver for Wireless Communications Technology," in *ACM SIGCOMM*, 2001.

[11] T. Liu, C. Sadler, P. Zhang and M. Martonosi, "Implementing software on resource-constrained mobile sensors: Experiences with Impala and ZebraNet," in *ACM MobiSYS*, 2004.

[12] C. Sharp, S. Schaffert, A. Woo, N. Sastry, C. Karlof, S. Sastry and D. Culler, "Design and implementation of a sensor network system for vehicle tracking and autonomous interception," in *IEEE EWSN*, 2005.

[13] MEMSIC, Inc, "MICAz Wireless Measurement System Datasheet, Revision A".

[14] MoteIV Corporation, "Tmote Sky: Datasheet," 2004.

[15] MEMSIC, Inc, "MDA 300 Data Acquisition Board Datasheet," Revision A.

[16] MEMSIC, Inc, "IRIS Wireless MEasurement System Datasheet, Revision A".

[17] T. W. Davis, X. Liang, M. Navarro, D. Bhatnagar and Y. Liang, "An Experimental Study of WSN Power Efficiency: MICAz with XMesh," *International Journal of Distributed Sensor Networks,* 2012.

[18] F. Stanjo, D. Cvrcek and M. Lewis, "Steel, cast iron and concrete: security engineering for real world wireless sensor networks," *Lecture Notes in Computer Science,* vol. 5037, pp. 460-478, 2008.

[19] M. Navarro, D. Bhatnagar and Y. Liang, "An Integrated Network and Data Management System for Heterogeneous WSNs," in *IEEE MASS*, 2011.

[20] MEMSIC, Inc, "XMesh User Manual, Revision A," 2010.