

I. INTRODUCTION

In present days of accelerated global climate change, ecologically fragile regions such as cold alpine areas have drawn increasing attention. Environmental monitoring and ecological protection has been given high priority in this region as the environment is extremely susceptible to climate change. However, field works in cold alpine areas are proved to be difficult and time-consuming as most of the sites are hard to reach. To facilitate environmental monitoring in such areas, new and effective technology gets applied [1]. Wireless sensor networks (WSN) were regarded as one of the most promising technologies in 21st century with outstanding advantages such as simple and easy deployment, long-term monitoring, less human intervention, and small, controllable, efficient and energy-saving system [2]. WSN applications to physically hard environment such as cold alpine areas will greatly mitigate problems encountered with traditional approaches, like huge man-power, high maintenance cost, and intensive field work. Literature review shows that the first WSN application for environmental monitoring appeared ten years ago [3]. In recent years, many studies had extended the WSN application to various fields and different environments. For example, Beutel [4] had set up a kind of sensor interface boards, known as PermaDAQ, to fit in an extreme environment in mountain permafrost region. Although trial deployment had shown that the system exhibited superior functionalities compared with traditional sensor networks, the data quality and system endurance still needs to be improved. Generally speaking, maintenances shall be with a minimum frequency when WSNs are deployed in a remote and hard to reach area. However, as inevitable annual snowfall or other severe climatic conditions in cold alpine areas always lay heavy burdens on the system, it will in fact encounter more damages and demand more maintenances compared with those in friendly environment. Thus, all WSN deployments in extreme environment shall face and try to solve such dilemma. Different solutions have been made on those issues, and various kinds of algorithms and software packages are developed to make WSN more reliable, efficient and robust. Cold and Arid Regions Environmental and Engineering Research Institute of Chinese Academy of Sciences (CAREERI/CAS) has set up two WSN applications to monitor hydrological and ecological variables in the non-populated Qilian mountains of West China. Based on those works, following sections will describe general information of the two applications and summarize experiences and lessons learned, as well as challenges we are facing. In section II, geographic

An area of 400 m by 400 m at the entrance of the Hulugou watershed was chosen and divided into 100 m by 100 m grids. After a series of laboratory testing and on-site testing, onboard sensors were set up to measure air temperature, relative humidity, radiation intensity, soil temperature and soil moisture in each grid. Data were collected at a prescribed interval and transmitted to nearby base station routed by a number of relay stations. The base station is responsible for remote node management as shown in Figure 2.

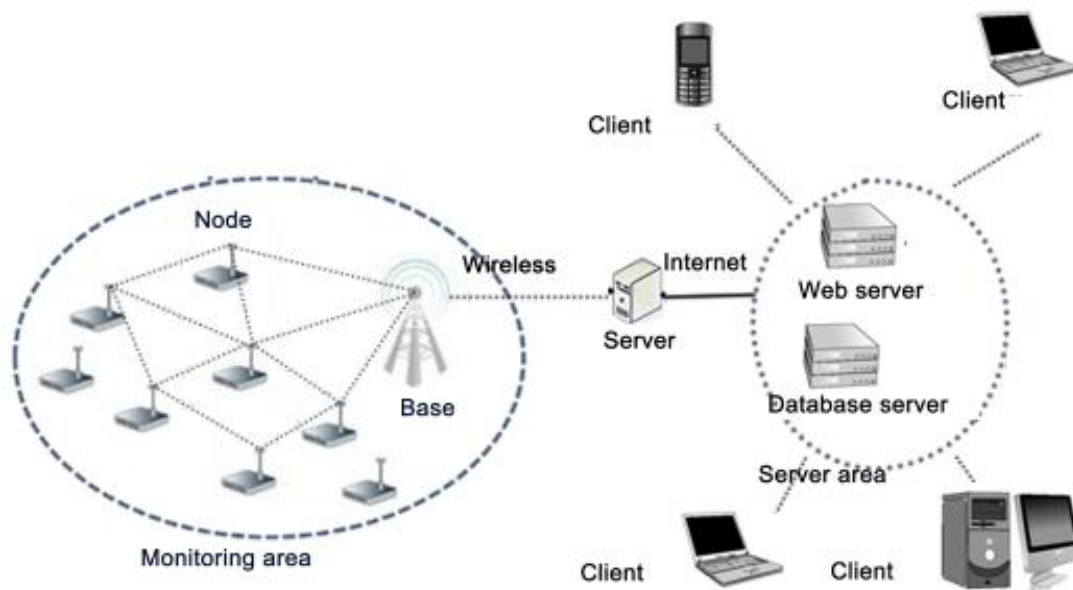


Figure 2. WSN deployment in the Hulugou watershed

b. Babaohe Watershed

The Babaohe watershed is located in the upstream area of the Heihe river basin. The river within the Babaohe watershed is 105 km long with a drainage area of around 2452 km² and an altitudinal range of 2640 to 5000m. It is of continental alpine climate and covered primarily with nature meadow like alpine meadow, grassland and others. Annual temperature varies from -30 to 20 Celsius degree. Annual precipitation is between 270 to 600 mm. Perennial snow coverage and permanent glaciers are discovered above 4200 m. Permafrost is distributed above 3600 m. The Babaohe watershed is an ideal site for cold region hydrology and remote sensing experiment. A set of observational instruments have been set up within this area as shown in Figure 3.

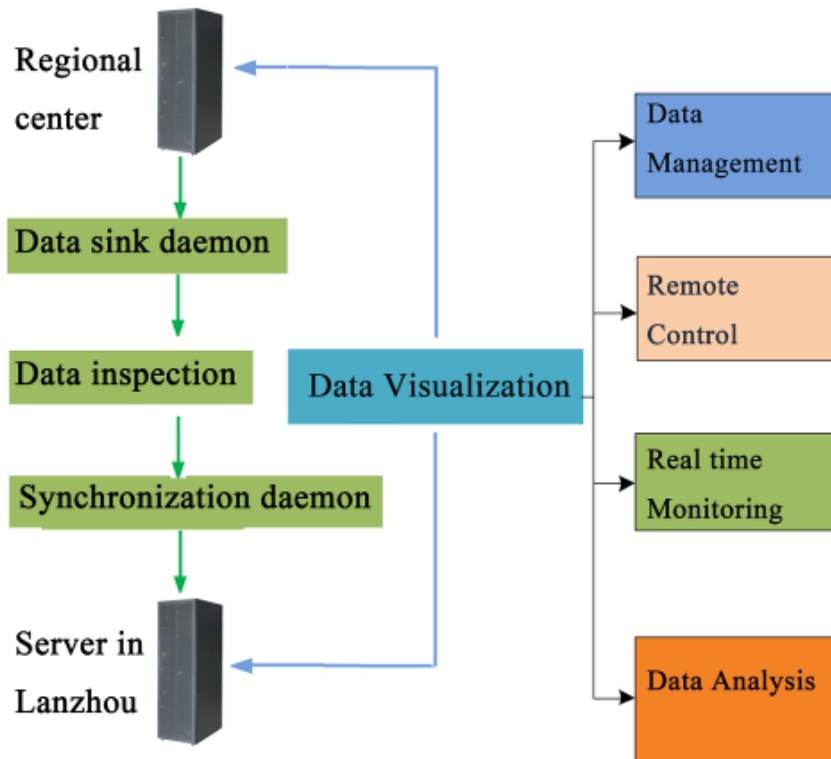


Figure 5. Automatic data exchange between regional center and the remote Lanzhou data server

An IPv6 based eco-hydrological WSN was designed to enhance existing instruments to obtain accurate precipitation, soil moisture content, soil temperature and snow cover data in an automation manner. After sufficient testing, the WSN has been officially put into use beginning August 2011. The successful deployment of eco-hydrological WSN in Babaohe watershed will offer convenient tools in exploring the water-heat process in alpine-cold region of west China.

The eco-hydrological WSN in the Babaohe watershed is based on 3-layer architecture, comprising of monitoring nodes, regional data server and the remote Lanzhou data center which brings together all sources of varied data besides those from WSN and is connected with WSN through Internet. A node management and data visualization system has been developed, residing in the three regional data servers and the remote data server in Lanzhou. With this system, researchers are able to monitor node status and manipulate nodes as well as to view incoming data in a visualized manner. The nodes, collecting meteorological, hydrological and ecological data with calibrated sensors, will transmit data wirelessly to regional data server. Monitoring nodes have been configured to accept remote commands from regional data server and remote

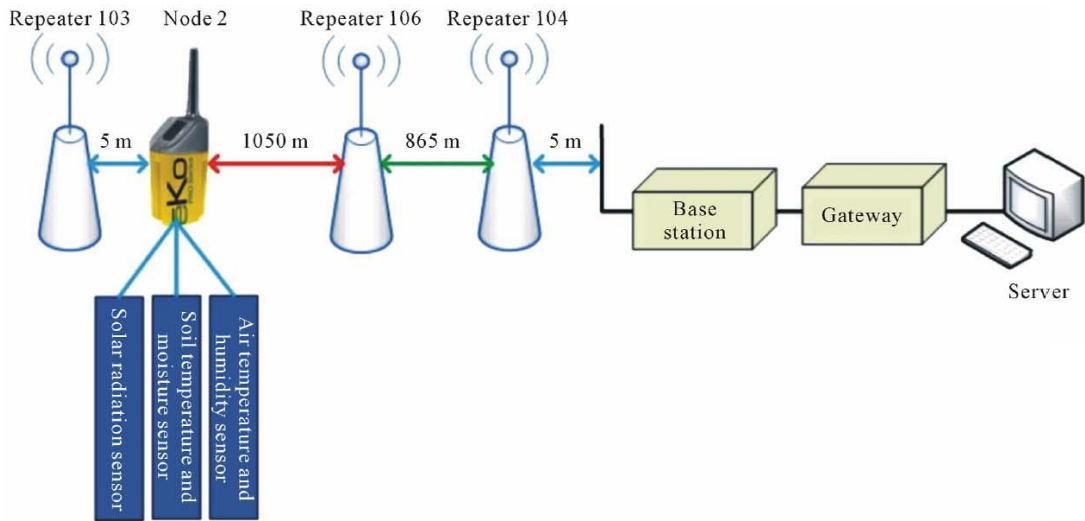


Figure 6. Network topology of WSN in the Hulugou watershed[7]

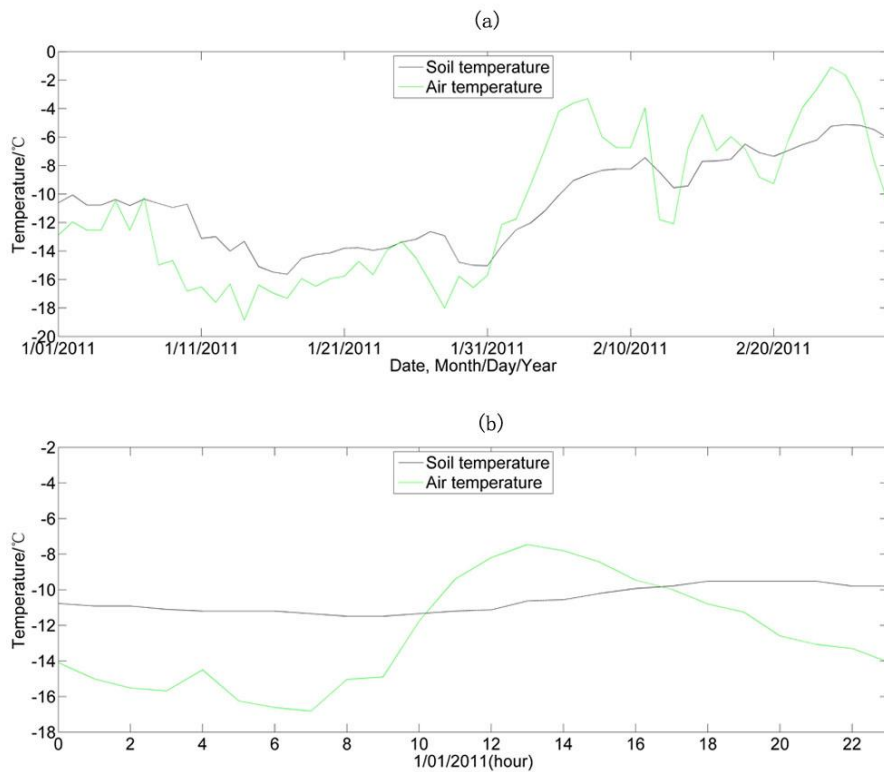


Figure 7. Variations of soil temperature and air temperature in the Hulugou watershed collected by the sensor Node2 (a) from 1/01/2011 to 2/28/2011 on daily average data, and (b) in 1/01/2011 on hourly average data



Figure 9. Device status monitoring interface in the data visualization and online management system for the Babaohe eco-hydrological WSN (presently only Chinese version available)

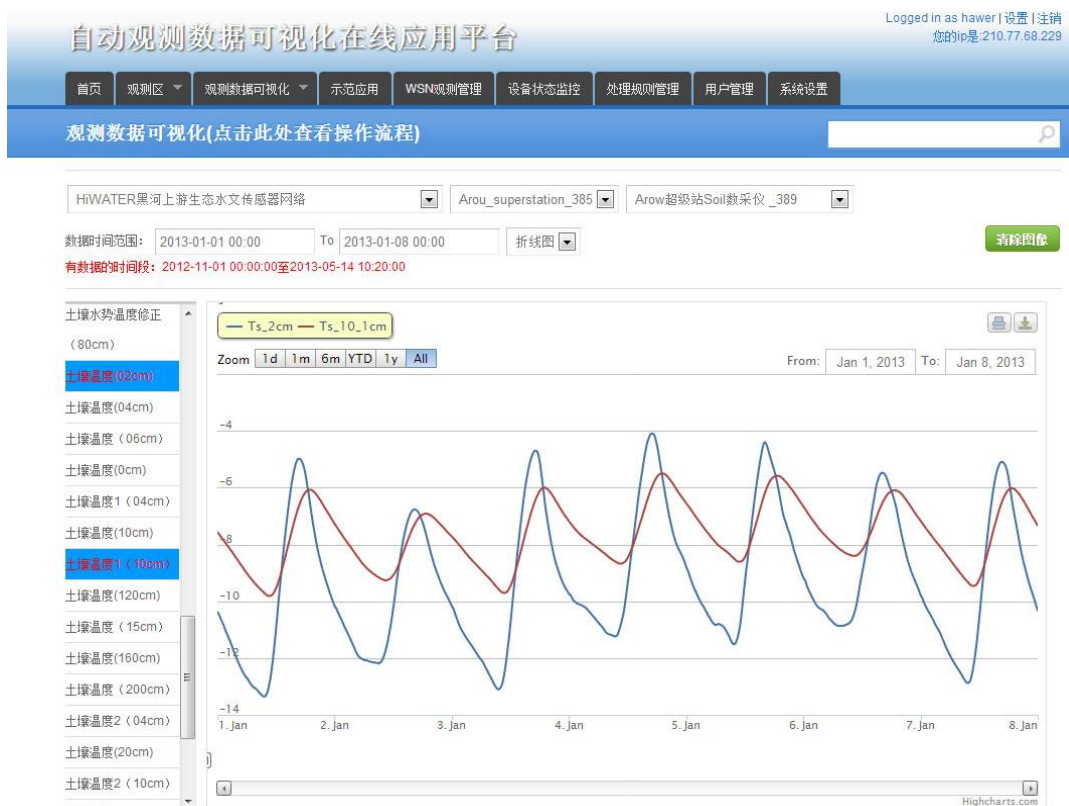


Figure 10. Online data monitoring in the data visualization and online management system for the Babaohe eco-hydrological WSN (presently only Chinese version available). The plot shows soil temperature at 2cm and 10cm acquired by the WSN from 01/01/2013 00:00 to 01/08/2013 00:00 (UTC+8)

Because of its dense node distribution, it is possible to make spatial maps for acquire variables. For example, Figure 11 presents seasonal variation of monthly average soil moisture and soil temperature at the depth of 10cm in the Babaohe watershed based on the data acquired by the Babaohe WSN. The figure was depicted with the Kriging interpolation method at a one kilometer resolution. As Figure 11 shows the distribution of 10cm soil moisture in January 2012, the Area1(Figure 11a) as indicated was one of the areas with lower moisture content, while in July 2012, Area1 (Figure 11b) changed into one of the areas with higher moisture content. By looking at the seasonal precipitation changes, the spatial heterogeneity like that presented in Area1 was related to the spatially uneven seasonal precipitation pattern in a cold and arid alpine mountain area. By contrast, the 10 cm soil temperature distribution presented (Figures 11c, d) a much similar spatial pattern in the Babaohe watershed for different seasons. The 10cm soil temperature in January 2012 was largely lower than that in July 2012 and areas with lower temperature in January 2012 were also lower in July. Such basic findings are consistent with what we understand in this mountainous area from previous studies and prove usefulness of WSN with unprecedented spatial and temporal resolutions

III. EXPERIENCES

From designing, testing to in situ installation and debugging of WSNs in cold alpine areas, we have encountered a lot of problems and learned many lessons. Great efforts have been made to ensure the link quality of network, reliability and integrity of data under extreme environment. Besides that, lowering total cost, energy efficiency and afterwards maintenance were also our concerns. In this section, we outlined a number of considerations and lessons learned from our practices.

a. Resistance to cold alpine conditions

The largest challenge posed by cold alpine area is the extremely low temperature. The endurance of sensors to subzero temperature is critical to the success of the outdoor deployment. In both deployments we used industrial level chips for sensors, which carry a RTC module with crystal oscillator and can ensure sound performance between -40 to 40 Celsius degrees. Those designs also guarantee an accurate system time.

watershed, a GPS module was added to each node to address the synchronization issue. Each node will make its time synchronized with satellite at given time slots.

d. Storage

Storage capacity and duration have to be considered to address potential network failure. In our both cases, data increment is not high and 6 months nodal data storage is sufficient. After a careful comparison among varied products, Samsung NAND 1GB flash memory was adopted. The major concern is its excellent built-in data integrity checking mechanism. By this mechanism, new data will be written twice, and the later writing will compare the former writing for integrity. When writing failure occurs, the bad storage page will be flagged and a new storage page will be allocated as replacement. Data can only be stored when no error is found in integrity checking process. Such checking process will greatly enhance data security at the cost of performance decrease. However, it is suitable for our WSN cases.

All acquired data will be stored in the NAND Flash memory until becoming full. Then new data will overwrite old one. 1GB is sufficient to hold data for 6 months in our cases. The architecture of its memory is shown in Figure 12.

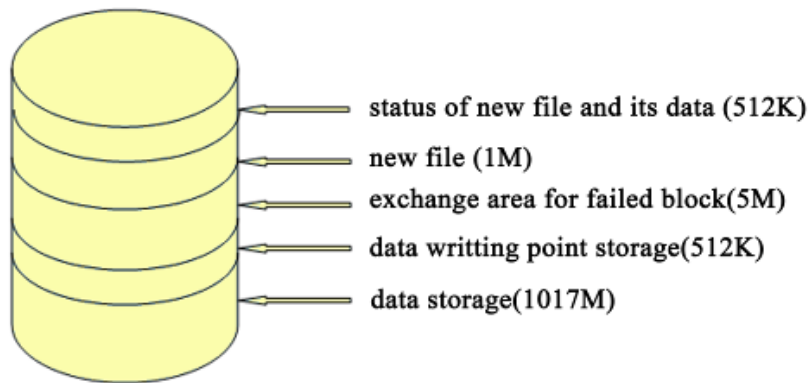


Figure 12. Architecture of the memory

e. Node routing

Aware of mountainous topography of the two sites, distance between nodes can vary from tens to hundreds meters, therefore multi-hop wireless network was adopted. Even so nodes and relays malfunctioned occasionally. This posed a challenge to us to design a well-organized network topology and routing scheme accounting for topographic condition. Excessive data flow at a single node and long distance between nodes may lead to poor link quality [10]. In our design of

data transmission rate and low cost. Data exchange between nodes and the wireless module and its control are implemented by Zigbee APIs (Application Programming Interface). Independent power management is set for the wireless module to avoid power accident.

- (2) For areas reached by mobile signal, GPRS (General Packet Radio Service) is preferred. Communication between base station and server is implemented by the GPRS module. Communication between GPRS and sensors is programmed by the AT command through serial ports. Independent power management is also set for this module.
- (3) For areas without mobile signal coverage, radio wave is used instead. This is useful especially in mountainous areas. The maximum transmission distance is up to 90 km, which might be shortened due to terrain or building obstacles.
- (4) For transference of large data such as images and videos, a microwave module is equipped, by which transmission distance can be up to over ten kilometers.
- (5) A VPN channel is used between each regional data servers and central remote data server to ensure real time data arrival to the central data center. However, in the current stage, we are using Internet connection from the regional data server to the Lanzhou central data center.

h. System integration

When WSNs are deployed in the cold alpine area, issues such as system incompatibility, unexpected malfunction, relevant calibration and upgrading issues may happen frequently [14, 15]. To deal with those problems, some proposed to develop their own integrated system to meet specific needs, including customized hardware, well-organized network topology, network protocol and even data structure [16]. Many attempts have been made in past researches. PermaDAQ [4], a system developed for permafrost monitoring on cold alpine sites, stands for a good example. To address the challenges confronted such as extremely low temperature and complex terrain condition, PermaDAQ used customized sensors, master board, as well as improved multi-hop protocol. As reported, the integrated PermaDAQ performed pretty well for permafrost monitoring purpose, although there still exist some issues, such as allocating voltage of master board in a more efficient manner.

In our applications, the embedded operating system ZKOS was used as the underlying platform, based on which tools and facilities were developed for cold alpine environment use. Commercial Campbell instruments and own-made wireless sensors were then integrated into this platform.

transference over the network will be less. By this means, the power consumption of data transmission will be greatly reduced.

c. Cost control and technical development

The fast development of WSN benefits from fast development of microcontroller, sensors, radio appliances and battery [18, 19]. Nowadays, those factors still constrain the extension of WSN applications in different scopes and make large-scale WSN with hundreds of sensors onboard unrealistic for financial and technical reasons. Because WSN is not a broad market to attract more commercial investments, we need to bring potential developments from other fields into WSN. 3G technology and new energy are most promising areas that might accelerate the development of WSN. Another attempt is to develop simple and useful software frameworks aiming at minimizing expertise needed in WSN development and deployment, which is helpful to a wide group of scientists who lack sophisticated computer skills from programming to hardware design. The philosophy of such applications is “keep it simple” as well as “make it effective and efficient”. In the past time, the Tiny Application Sensor Kit (TASK) [20], a system designed for end-users in sensor network deployment and management, is one of the most successful systems in this direction and has attracted many followers. Developed by the support of the TinyOS community, TASK can greatly reduce the requirement and complexity of general WSN deployment and management with its compacted service kit, convenient portal interface and acceptable remote management accuracy. Based on such works, Barrenetxea [21, 22] has developed SensorScope. SensorScope has employed multiple gateways and integrated the whole workflow within a real-time Google Maps-based Web interface. With such functionalities, it can greatly reduce the costs and complexity of the whole WSN systems with favorable adaptability to difficult environment. Although challenges such as sensor calibration still need better solution, it has already opened an optimistic direction and showed great potential in the future.

V. CONCLUSIONS

As a newly emerged and promising technology, WSN applications in cold alpine areas with physically hard conditions is proved to be successful. Our applications in both the Hulugou watershed and Babaohe watershed have acquired successive and reliable data. It shows that WSN

recovery in environmental extremes”, 2009 International conference on Information Processing in Sensor Networks, IPSN 2009, pp. 265-276, San Francisco, USA, Apr. 13-16, 2009.

[5] R. S. Chen and C. T. Han, “Hydrology, ecology and climate significance and its research progress of the alpine cold desert”, *Advance in Earth Science*, Vol. 25, No. 3, pp. 255-263, March 2010.

[6] W. P. Zhu, Y. N. Zhang and L. H. Luo, “Study and application of the wireless sensor network to eco-hydrology”, *Journal of Glaciology and Geocryology*, Vol. 33, No. 3, pp. 573-581, June 2011.

[7] Y. N. Zhang, L. H. Luo, J. Y. Huo and W. P. Zhu, “An eco-hydrology wireless sensor demonstration network in high-altitude and alpine environment in the Heihe River Basin of China”, *Wireless Sensor Network*, Vol. 4, No. 5, pp.138-146, May 2012.

[8] H. Abrach, S. Bhatti, J. Carlson, H. Dai, J. Rose, A. Sheth, B. Shucker, J. Deng and R. Han, “MANTIS: System support for multimodal networks of In-situ Sensors”, *Proc. of the 2nd ACM International Workshop on Wireless Sensor Networks and Applications, WSNA 2003*, pp. 50-59, San Diego, USA, Mar. 22-24, 2003.

[9] A. Cerpa, N. Busek and D. Estrin, “SCALE: A tool for simple connectivity assessment in lossy environments”, *CENS Technical Report # 21*, pp. 1-16, 2003.

[10] W. Y. Fu, D. S. Li, J. Chen, Y. Y. Han and J. G. Nie, “Topology optimization control with balanced energy and load in underwater acoustic sensor networks”, *International Journal on Smart Sensing and Intelligent Systems*, Vol. 4, No. 1, pp. 138-159, March 2011.

[11] P. Juang, H. Oki, Y. Wang, M. Martonosi, L. Peh and D. Rubenstein, “Energy-efficient computing for wildlife tracking: design tradeoffs and early experiences with Zebrantet,” *ACM Sigplan Notices*, Vol. 37, No. 10, pp. 96-107, October 2002.

[12] A. Arora, P. Dutta, S. Bapat, V. Kulathumani, H. Zhang, V. Naik, V. Mittal, H. Cao, M. Demirbas, M. Gouda, Y. Choi, T. Herman, S. Kulkarni, U. Arumugam, M. Nesterenko, A. Vora and M. Miyashita, “A line in the sand: a wireless sensor network for target detection, classification, and tracking”, *Computer Networks*, Vol. 46, No. 5, pp.605-634, December 2004.

[13] T. W. Sung, T. T. Wu, C. S. Yang and Y. M. Huang, “Reliable data broadcast for Zigbee wireless sensor networks”, *International Journal on Smart Sensing and Intelligent Systems*, Vol. 3, No. 3, pp. 504-520, September 2010.

- [14] A. Hasler, I. Talzi, J. Beutel, C. Tschudin and S. Gruber, "Wireless sensor networks in permafrost research:concept, requirements, implementation, and challenges", 9th International Conference on Permafrost, pp. 669-674, Fairbanks, USA, Jun. 29-Jul. 3, 2008.
- [15] K. Martinez, P. Padhy, A. Elsaify, G. Zou, A. Riddoch, J. K. Hart and H. L. R. Ong, "Deploying a sensor network in an extreme environment", IEEE International Conference on Sensor Networks, Ubiquitous, and Trustworthy Computing, Vol. 1, pp. 186-193, Tai Chung, Taiwan, Jun. 5-7, 2006.
- [16] K. Aberer, M. Hauswirth and A. Salehi, "A middleware for fast and flexible sensor network deployment", Proc. of the 32nd International Conference on Very Large Databases, pp. 1199-1202, Seoul, South Korea, Sep. 12-15, 2006.
- [17] S. Bandyopadhyay and E. J. Coyle, "An energy efficient hierarchical clustering algorithm for wireless sensor networks", Proc. of the Conference on Computer Communications, IEEE INFOCOM 2003, Vol. 1-3, pp. 1713-1723, San Francisco, USA, Mar. 30-Apr. 3, 2003.
- [18] P. Corke, T. Wark, R. Jurdak, H. Wen, P. Valencia and D. Moore, "Environmental wireless sensor networks", Proceedings of the IEEE, Vol. 98, No. 11, pp. 1903-1917, November 2010.
- [19] A. Rahman and S. Asokan, "Fiber Bragg grating sensors: new ideas on strain-temperature discrimination", International Journal on Smart Sensing and Intelligent Systems, Vol. 3, No. 1, pp. 108-117, March 2010.
- [20] P. Buonadonna, D. Gay, J. M. Hellerstein, W. Hong and S. Madden, "TASK: Sensor network in a box", Proceedings of the Second European Workshop on Wireless Sensor Networks, pp. 133-144, Istanbul, Turkey, Jan. 31-Feb. 2, 2005.
- [21] G. Barrenetxea, F. Ingelrest, G. Schaefer, M. Vetterli, O. Couach and M. Parlange, "Sensorscope: Out-of-the-box environmental monitoring", Proc. of the International Symposium on Information Processing Sensor Networks, pp. 332-343, St Louis, USA, Apr. 22-24, 2008.
- [22] F. Ingelrest, G. Barrenetxea, G. Schaefer, M. Vetterli, O. Couach and M. Parlange, "SensorScope: Application-specific sensor network for environmental monitoring", ACM Transactions on Sensor Networks, Vol. 6, No. 2, pp. 1-32, February 2010.