Least Impact Routing towards Sustainable Sensor Networks Enhanced by Energy Harvesting

K. Takahashi*, M. Bandai*, H. P. Tan**, W. K.G. Seah*** and T. Watanabe*

*Graduate School of Informatics, Shizuoka University
3-5-1, Johoku, Hamamatsu-Shi, Shizuoka, 432-8011, Japan, watanabe@aurum.cs.inf.shizuoka.ac.jp
**Networking Protocols Department, Institute for Infocomm Research, Singapore,
hptan@i2r.a-star.edu.sg
***School of Engineering and Computer Science, Victoria University of Wellington, New Zealand
Winston.Seah@ecs.vuw.ac.nz

ABSTRACT

Wireless Sensor Networks (WSNs) have become one of the key technologies for natural environment monitoring. However, replacing nodes may incur negative impact, as a result of damage to nature caused by humans, equipment and vehicles. This paper considers sustainable sensor networks for nature monitoring with low impact on nature by information and communication technologies. To minimize the impact, we propose a routing protocol called Less Impact patch Concentration Routing protocol (LICR). In addition, we propose an enhanced version of LICR using energy Harvesting Driven (HD) nodes. The results from the performance evaluation show that LICR and HD-enhanced LICR have less adverse impact on the natural environment.

Keywords: Wireless Sensor Networks, Natural Environment Monitoring, Multi-hop Routing, Energy Harvesting

1 INTRODUCTION

In recent years, Wireless Sensor Networks (WSNs) have become one of the key technologies for realizing a ubiquitous computing society. WSNs can be deployed in various fields, for instance, monitoring and surveillance, medical and healthcare applications, and disaster-prevention [1]. Among them, natural environment monitoring is one of the promising and significant applications that solve various environmental problems [2]. When developing WSNs for natural environment monitoring, we should consider how sensor networks affect nature. If sensor nodes contain toxic materials, they pose a potential threat and could negatively impact the natural environment. Moreover, nodes have limited battery power due to the hardware limitations. Even conventional power saving schemes such as clustering and sleep scheduling [3][4][5] are limited and replacing nodes is unavoidable. The process of replacing nodes by humans or mechanical means could inherently affect the natural environment. On the other hand, one way to avoid damage to nature is to introduce energy harvesting nodes in WSNs. These nodes can harvest ambient energy from the environment to recharge the batteries. Although these nodes are maintenance-free, their ability to harvest sufficient energy from the environment depends on many environmental factors [6] and may lead to intermittent operation. Thus, in addition to improving network performance, sensor networks should be designed to prevent, mitigate or at least manage the negative impact on nature.

In this paper, we investigate sustainable sensor networks for nature monitoring with low impact on nature. First, we formalize a model for the natural environment. Next, we propose a routing protocol, called Less Impact patch Concentration Routing protocol (LICR). Following this, we introduce energy Harvesting Driven nodes to LICR. The analytical and quantitative results show that LICR reduces the negative impact on the natural environment and HD-enhanced LICR produces a complementary effect and reduces the defects which each kind of nodes have.

2 FORMULIZATION OF IMPACT TO NATURAL ENVIRONMENT

We assume that the impact on natural environment depends on the amount of nature. In Figure 1, nodes in areas abundant with nature such as forests incur greater impact, while those in other areas such as paved road incur less impact. Based on the idea, this paper formalizes the impact of WSNs on the natural environment.

2.1 Definitions

First, we denote the amount of nature in an area as $V_{(t)}$, where t is time. There are two possible ways to calculate V. One is to measure the actual quantity of resource. The other way is to estimate the amount of vegetation using some surveys. In both cases, $V_{(t)}$ is non-negative value.

Next, we consider the following key factors which affect the natural environment: (i) damage due to existence of sensor nodes and by humans during maintenance (negative) and (ii) natural recovery and growth (positive). To quantify these factors, we consider a WSN placed in a certain area s.

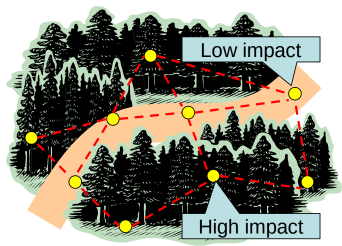


Figure 1. Degree of impact on natural environment

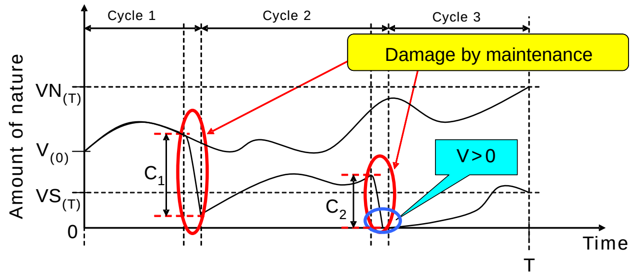


Figure 2 Change of amount of nature *V*

We define the duration of cycle *q*, t_q, as the sum of the operating time and maintenance time. Figure 2 shows some examples. Assuming the total destruction rate is *D* and the total growth is *G*, the net growth *C* is derived as:

$$C_{(t_q)} = G_{(t_q)} - D_{(t_q)} \quad (1)$$

, where a smaller *C* means greater damage to the natural environment.

2.2 Impact on Natural Environment: INE

First, we investigate the change of the amount of nature *V* in a situation where no sensor networks exist in an area. Accordingly, the amount of nature at time *T*, denoted as $VN_{(T)}$, is given as follows:

$$VN_{(T)} = V_{(0)} + G_{(T)} \quad (2)$$

In the presence of a sensor network, the extent of damage to the natural environment is higher during maintenance than during operation as people need to enter the area. The corresponding amount of nature at time T, denoted as $VS_{(T)}$, is given as follows:

$$VS_{(T)} = \max(0, V_{(0)} + \sum_{i=1}^{n} C_{t_i}) \quad (3)$$

Next, using Eqs. 2 and 3, we derive the Impact on Natural Environment (INE). A larger *INE* means more negative impact on the natural environment. *INE* at time *T* is defined as the followed ratio:

$$INE_{(T)} = \frac{VN_{(T)} - VS_{(T)}}{VN_{(T)}} \quad (4)$$

The larger the difference between $VN_{(T)}$ and $VS_{(T)}$, the larger *INE* is, which indicates that the impact of sensor networks on natural environment is significant. Using Eq. 4, we extend the above formulation to the situation where *K* areas exist in a network. Therefore, we obtain:

$$INE_{all(T)} = \frac{\sum_{i=0}^{K-1} VN_{i(T)} - VS_{i(T)}}{\sum_{i=0}^{K-1} VN_{i(T)}} \quad (5)$$

3 PROPOSED ROUTING PROTOCOL

In this section, we propose a new routing protocol called Less Impact patch Concentration Routing (LICR) protocol to reduce the impact of WSN on the natural environment. The basic idea of LICR is discussed in R'09 Twin World Congress [7]. In this paper, we use two types of node: (i) Battery powered Driven node (BD-node) and (ii) energy Harvesting Driven node (HD-node). Using these nodes, we propose two types of protocol based on LICR. These protocols are:

1) LICR with BD-nodes (LICR-BD)
2) LICR with BD-nodes and HD-nodes (LICR-BHD)

3.1 LICR-BD

LICR-BD divides an area into multiple patches and directs traffic through certain patches that have small $V_{(0)}$. These patches are called LI patches. Nodes in LI Patches that are routing traffic transmit more data, leading to earlier battery depletion. As a result, the level of node maintenance increases in LI patches. At the same time, since nodes in non-LI patches transmit less data, the corresponding power consumption is lower. The impact of maintenance in LI patch is much less than that in non-LI patch because the amount of nature is lower bounded by 0 as defined in section 2.1. Therefore, increasing the level of maintenance in LI patch by LICR-BD protocol can reduce impact on the natural environment in whole area.

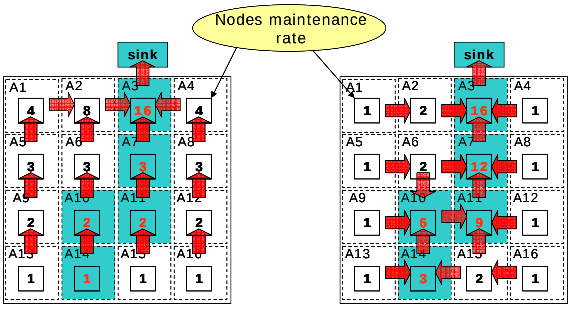
We illustrate the concept of LICR-BD in Figure 3(b). The area is divided into 16 patches called A1 to A16. We assume LI patches are A3, A7, A10, A11 and A14. Data traffic flows in the direction of the arrows towards the sink. We assume that the data generation rate in each patch is 1 and the node maintenance rate is shown in the square of each patch, where it is higher in LI patches compared to non-LI patches. In LICR-BD, by directing data traffic to LI patches, the power consumption is distributed across patches. As a result, the sum of the damage due to node maintenance in all patches is reduced. Thus, LICR-BD can reduce impact on natural environment of the area.

3.2 LICR-BHD

As BD-nodes have limited energy source and battery depletion can occur, node maintenance is an essential issue. However, if the nodes can get power from ambient environment, they can operate for a long time without maintenance. In this section, we discuss LICR with heterogeneous nodes, BD-nodes and HD-nodes, called LICR-BHD. It is designed to exploit the benefits of BD-nodes and HD-nodes while overcoming their deficiencies.

Using renewable energy for WSNs is not a new concept. This energy includes solar, wind, water, thermal and vibration energy. This energy is harvested by energy harvesting devices to generate electric energy. WSNs that are composed of HD-nodes operate for much longer durations such as years or even decades after deployment.

Figure 4 shows the difference in the energy consumption models of BD-node and HD-node. In WSNs using HD-nodes, the most important problem is when these nodes can harvest enough energy from energy harvesting devices. In Figure 4, each HD-node communicates with other nodes only during discharge/consumption periods. The duration of each charging period depends on the energy harvesting rate. If there is no energy harvesting source in the vicinity of the node, it cannot harvest any energy. Therefore, the charging duration of each HD-node is non-deterministic and depends on environmental factors. Hence, it is difficult for nodes to



(a) Conventional (b) Proposed: LICR

Figure 3. Nodes maintenance rate of each patch

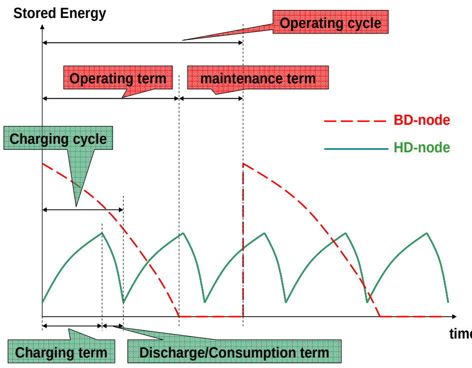


Figure 4. Characteristic of Power Consumption

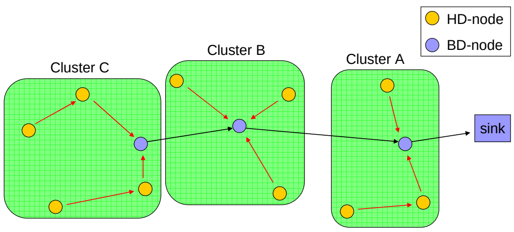


Figure 5. Cluster String Topology

ensure that other nodes around them are awake to communicate. Since scheduling schemes such as sleep-scheduling for WSNs are unusable, broadcast, geographic and opportunistic schemes are more suitable in WSNs using HD-nodes. In fact, in our opinion, delay-tolerant network (DTN) techniques are particularly appropriate.

By deploying HD-nodes in LI patches and applying LICR, we can reap the following benefits:

1) HD-nodes in LI patches can communicate effectively because of few natural obstacles in these patches;
2) HD-nodes in LI patches can get higher charging rate than HD-nodes in non-LI patches because of direct exposure to solar and wind.

In LICR-BHD, we can benefit from the use of HD-nodes while diminishing the defects of both BD-node and HD-node. Let's consider the communication between both types of nodes. Assuming that BD-nodes are always active and can receive packets, then HD-nodes can send to BD-nodes anytime, although this may lead to higher power consumption in the latter. In LICR-BHD, we propose Cluster String Topology (CST), which is a routing protocol for heterogeneous nodes. Figure 5 shows a concept of CST.

4 EVALUATION

We evaluate the performance of these proposed protocols by analysis. We show the quantitative evaluation of LICR-BD and the qualitative evaluations of LICR-BHD.

4.1 Quantitative Evaluation of LICR-BD

We evaluate the performance of the proposed LICR-BD protocol by analysis. We adopt the shortest path routing as the conventional protocol. We evaluate the performance in terms of the sum of all areas Impact on Natural Environment, INE_{all}. Figure 3 shows the data flow and rate of node maintenance of the conventional protocol and proposed one. We assume the following:

1) There are enough nodes in each patch, and nodes can communicate with those in adjacent patches.
2) $C_{(t_i)}$ is a constant C in all patches.
3) The initial amount of V at all LI patches is 100
4) The initial amount of V at all non-LI patches is 500
5) The number of maintenance of each patch is proportional to node maintenance rate.

Using these assumptions, we evaluate INE_{all} for LICR-BD and shortest path routing for various total number of maintenance, n and present the results in Figure 7. When C is -100, INE_{all} of LICR-BD is 34 percent smaller at n=60, and 44 percent smaller at n=90 than that of the conventional algorithm. This result means that LICR-BD can reduce the impact on the natural environment. In addition, the benefits become larger as the number of maintenance or the extent of damage becomes larger.

4.2 Qualitative Evaluation

In table 1, we show the qualitative evaluation of LICR-BHD as well as the shortest path routing and LICR-BD in four aspects: impact on natural environment, throughput, robustness and lifetime.

In terms of impact on natural environment, LICR-BD requires maintenance that involves people entering the area. Although LICR-BD has less impact than the conventional protocol, it still incurs some negative impact on natural environment. While maintenance is also needed by LICR-BHD, it is only performed in LI patches where BD-nodes are deployed. This reduces the impact on the whole area because we enter only LI patches that have low amount of nature. Therefore, LICR-BHD is better for natural environment than LICR-BD.

In terms of throughput, LICR-BD is expected to perform better. Although each BD-node requires some maintenance, it transmits and receives data effectively by resending immediately and scheduling in the duration of operation. With LICR-BHD, each HD-node needs long energy charging duration that depends on environmental factors. However, BD-nodes in LI patches can cover the HD-node's communication when it is charging, thereby preventing a drop in throughput.

Table 1. Qualitative evaluation of three protocols

	Shortest path routing	LICR-BD	LICR-BHD
Impact on natural environment	Not good: significant negative impact	Good: reduce negative impact	Good: only some nodes need maintenance
Throughput	Good: nodes communicate anytime	Better: nodes communicate more effectively	Good: BD-nodes cover HD-node's transmission during charging time
Robustness	Good: operate consistently as long as node's battery is alive	Good: operate consistently as long as node's battery is alive	Good: each kind of nodes operates effectively by optimized distribution
Network lifetime	Not good: nodes die when battery is depleted	Not good: certain nodes need more maintenance	Good: some nodes operate without maintenance

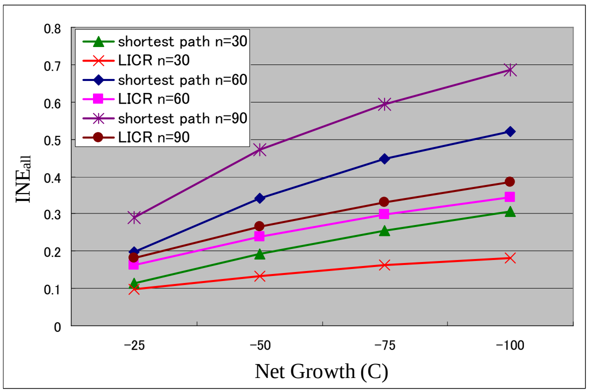


Figure 7. Difference of Impact on Natural Environment (INE) between two protocols

From the point of view of robustness, LICR-BD can operate consistently as long as the BD-node's battery is alive. When the battery is depleted, the node or the patch may be of no use until the maintenance finishes. On the other hand, HD-node's battery is rechargeable. However, the energy harvesting rate of the HD-node depends on environmental factors in its vicinity, i.e., each HD-node is highly dependent on surrounding conditions. In LICR-BHD, the effects of these surrounding conditions are reduced and limited to patches that comprise HD-nodes. Additionally, deploying BD-nodes to the patches where data traffic is concentrated makes the protocol more stable.

From the point of view of network lifetime, LICR-BD requires more maintenance for nodes in LI patches. It leads to frequent interruptions and reduced lifetime. While LICR-BHD also requires more maintenance in these patches, the maintenance required in non-LI patches is reduced because of the use of HD-nodes. As a result, it achieves longer lifetime than LICR-BD.

As shown above, LICR-BD is appropriate for delay sensitive applications such as disaster-prevention monitoring. LICR-BHD preserves the natural environment by using HD-nodes while overcoming the limitations of communication reliability by BD-nodes. It produces a complementary effect between BD-nodes and HD-nodes.

5 CONCLUSION AND FUTURE WORK

In this paper, we investigated sustainable wireless sensor networks for nature monitoring with low impact on nature by information and communication technologies. First, we defined the amount of nature and factors such as damage and growth that affect it. Based on these definitions, we defined the formalized impact *INE*. To minimize the impact, we proposed a routing protocol called Less Impact area Concentration Routing protocol (LICR). The result of quantitative evaluation showed that LICR achieved about 40 percent less impact compared with the shortest path routing protocol. We then proposed LICR-BHD, which is an enhanced version of LICR with energy Harvesting Driven nodes (HD-nodes). We compared LICR-BHD with LICR-BD. LICR-BHD preserves the natural environment while accounting for the limitation of communication reliability. It balances the trade-off between the impact on natural environment and communication efficiency.

In the future, we will investigate how to decide between LI patch and non-LI patch. We should also consider details of the routing algorithm of LICR-BHD as well as that of LICR-BD.

REFERENCES

[1] Ian F. Akyildiz, Weilian Su, Yogesh Sankarasubramanian and Erdial Cayircl, A Survey on Sensor Networks, IEEE Communications Magazine, pp.102-114 (2002)

[2] J. K. Hart and K. Martinz, Environmental Sensor Networks: A revolution in the earth system science?, Earth-Science Reviews 78, pp.177-191 (2006)

[3] W. B. Heinzelman, A. P. Chandrakasan and H. Balakrishnan, An Application-Specific Protocol Architecture for Wireless Microsensor Networks, IEEE Transactions on Wireless Communications, pp.660 - 670 (2002)

[4] C. Intanagonwiwat, R.Govindan and D. Estrin, Directed Diffusion: A Scalable and Robust Communication Paradigm for Sensor Networks, Proc. ACM Mobicom'00, pp.55-67 (2000)

[5] W.Ye, J. Heidemann and D. Estrin, Medium Access Control with Coordinated, Adaptive Sleeping for Wireless Sensor Networks, IEEE/ACM Transactions on Networking, pp.493-506 (2004)

[6] W. K. G. Seah, Z. A. Eu and H. P. Tan, Wireless Sensor Networks Powered by Ambient Energy Harvesting – Survey and Challenges, Wireless VITAE, invited paper (2009)

[7] K. Takahashi, M. Bandai and T. Watanabe, A Routing Protocol towards Sustainable Sensor Networks for Nature Monitoring, Conference CD-ROM, Resource Management and Technology for Material and Energy Efficiency (R'09)