Accessing Data Transfer Reliability for Duty Cycled Mobile Wireless Sensor Network

FAISAL KARIM SHAIKH*, ABDUL QADIR ANSARI**, AND NAEEM AHMED MAHOTO***

RECEIVED ON 28.09.2013 ACCEPTED ON 09.01.2014

ABSTRACT

Mobility in WSNs (Wireless Sensor Networks) introduces significant challenges which do not arise in static WSNs. Reliable data transport is an important aspect of attaining consistency and QoS (Quality of Service) in several applications of MWSNs (Mobile Wireless Sensor Networks). It is important to understand how each of the wireless sensor networking characteristics such as duty cycling, collisions, contention and mobility affects the reliability of data transfer. If reliability is not managed well, the MWSN can suffer from overheads which reduce its applicability in the real world. In this paper, reliability assessment is being studied by deploying MWSN in different indoor and outdoor scenarios with various duty cycles of the motes and speeds of the mobile mote. Results show that the reliability is greatly affected by the duty cycled motes and the mobility using inherent broadcast mechanisms.

Key Words: **Wireless Sensor Network, Mobile Wireless Sensor Networks, Duty Cycle Wireless Sensor Networks.**

1. INTRODUCTION

The traditional WSN architecture consists of a large number of static sensor motes which are densely deployed over an area of interest. Sensor motes are tiny, battery-operated computing devices operational with sensors capable of sensing information from their surroundings. Sensor motes collect data from their surroundings, process them locally and send the results to a data collecting point, usually called as a base station. In past WSNs were deployed in a hostile environment for military surveillance in order to collect information about the opponent actions. Later on, due to WSN applicability, it becomes a convenient tool for environmental monitoring [1], utility metering [2] and many other applications [3]. Additionally, the cost for processing power and wireless communication started to decrease which eventually made WSNs more reasonable and more attractive [4]. Generally, the radio range of sensor motes is less and the communication paradigm between the sensors motes and the base-station is multi-hop.

* Associate Professor, Department of Telecommunication Engineering, Mehran University of Engineering & Technology, Jamshoro.
** Senior Manager Multimedia and Broadband, Pakistan Telecommunication Company Limited, Hyderabad.
*** Assistant Professor, Department of Software Engineering, Mehran University of Engineering & Technology, Jamshoro.

WSNs often do not work as anticipated when deployed in the real world due to many reasons such as environmental influence can result a non-deterministic performance of sensor motes. Similarly, radio communication may affect the overall performance of data transfer, i.e. interference and collisions because of the multihop communication paradigm. On the other hand, in order to save the energy duty cycling in the WSNs is a common approach where sensor motes go in to sleep mode after performing some tasks. Duty cycling is better to achieve the energy savings in WSNs but it hinders in smooth data transfer since the mote may be in sleep mode when the mobile or some other node sends the data. Alongside, the mobility itself may also hinder in the data transfer where it is difficult to know the presence of the mobile node and also the fading effects of wireless communication.

The traffic pattern inherent to WSNs is convergecast [5-6], i.e. data generated from the sensor motes is transported towards the base station. As a consequence, motes closer to the base station are more overloaded than others, and subject to premature energy depletion. This issue is known as the funneling effect [7-9]. In order to overcome the funneling effect redundant nodes are deployed around the base station. Increasing the number of motes will not only increase the cost of the network but also increase the collisions and contention. Thus, the data may not be transported properly. The failures relevant to the data transport include data loss and higher delays. These failures directly impact the responsiveness, i.e. reliability and timeliness of data transport in WSNs. The problems mentioned above can be improved by introducing the mobility in WSNs [1, 10, 11]. Instead of collecting data through Multihop, the mobile nodes can visit static motes in the network and collect/send data directly through single-hop transmission. This will not only reduce the contention and collisions, but will also reduce the message loss. The single-hop transmission also helps in reducing the funneling effect, as mobile motes can visit different regions in the network and spread the energy consumption more uniformly even in the case of a dense WSN architecture. Generally, the mobile WSNs can be adapted easily for delay-tolerant applications [12]. Mobility can also be exploited in scenarios where motes are attached to mobile objects such as humans [13] and animals (e.g. zebras [14] or rats [15]).

Apart from the issues mentioned above another major issue with WSNs is of reconfiguration. As after deploying the WSN some or all of the static motes need reconfiguration. Generally, the base-station mote broadcast new parameters and configuration updates to its neighbor motes. In response to that the neighbor motes further broadcast the reconfiguration messages to their neighbors and by this way all motes or subset of motes are updated. This process of updating the network requires lot of messages to be exchanged across the network. In order to encounter this problem, the mobile motes can be programmed in such a way that it sends the new parameters only to those static mote where it is mandatory hence reducing the overhead. The work presented in this research is solemnly based on assessing data reliability in MWSN. It is crucial to evaluate the factors due to which the number of messages is correctly transferred between mobile and static motes.

The remainder of the paper is organized as follows. Section 2 proceeds with the related work followed by methodology and experimental environments used for assessing the data reliability in Section 3. Section 4 presents the results while Section 5 concludes the paper.

2. RELATED WORK

The study of reliable data transport in WSNs has been the subject of extensive research during the last decade [16-22]. More recently mobility has also been introduced to WSNs. In fact, mobility in WSNs is useful for several reasons, e.g. cost, connectivity, reliability and energy efficiency [10, 23]. Nowadays, testbeds are even created for the support of mobility in WSN such as Sensei-UU [24].

The limited body of work exists for assessing the data reliability in mobile WSN. The reliability issue in mobile WSNs is presented in [25]. The authors in [25] presented a system for data collection from sparse sensor networks with the help of mobile relays. Zhao, et. al. [26] proposed a message ferrying approach for data delivery in sparse mobile Ad hoc networks. DiFranceso, et. al. [10] authors have provided an extensive survey by giving a comprehensive taxonomy of mobile WSN architectures and as well as presented an overview of the data collection process. Navid, et. al. [27], the authors have demonstrated the data collection from mobile motes in scenarios where all motes, both base station and sources, are mobile.

On the other hand, duty cycling is very popular in order to conserve the energy of sensor motes [28]. Sensor motes can perform duty cycling as per some schedule or on demand when some user data needs to be delivered. The idea behind ondemand approaches is that the sensor node should be awakened before the data arrives from the neighboring node. Generally, two different channels are used, i.e., a data channel (for normal data transfer) and a wake up channel. Some scheduled duty cycling strategies require that all neighboring nodes wake up at the same time [29-30] while some other strategies avoid the tight synchronization and allow each node to wake up independently [31-32]. When nodes are awakened synchronously, multiple paths between a source and a destination are possible. In contrast, when sensor nodes are awakened independently, the forwarding path may suffer high latency because the other sensor nodes along the path may not be available during the same time period.

The above approaches are limited in the sense that they are only considering the collection of data from the static sensor motes. They do not consider data transfer from mobile mote to the static nodes (e.g. for reconfiguring the parameters). Also, the duty cycling is only exploited for routing purposes. To the best of our knowledge duty cycling is not explored for mobility scenarios.

From the above discussion it is evident that there is a need for assessing the data reliability in MWSN when particularly the mobile mote transfers the data or the parameters to the duty cycled static motes.

3. METHODOLOGY AND EXPERIMENTAL ENVIRONMENT

3.1 Methodology

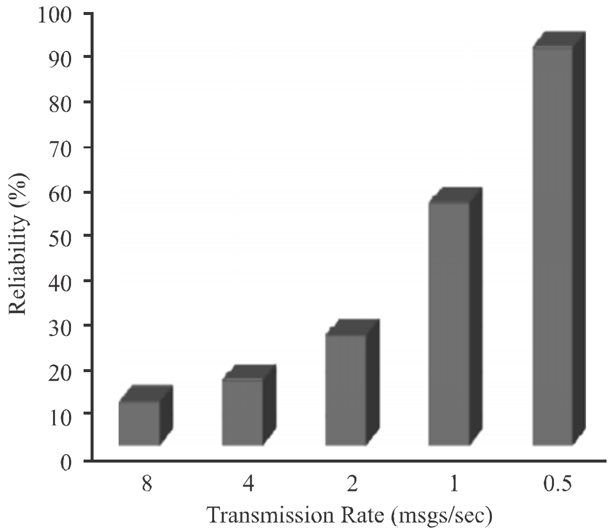
In order to evaluate the reliability of the mobile WSNs with duty cycled sensor nodes a test bed of eight Mica2 motes running the TinyOS operating system [33], and laptops running Windows XP attached with Mica2 and MIB510 serving as a base station are used. Various indoor and outdoor experiments were performed having different speeds of mobile node and different duty cycles for the sensor nodes. In order to improve the measurement precision of Mica2 motes a system called virtual ground is used. In virtual ground, each Mica2 mote has a small plastic cup below it so that the antenna sees an equipotential surface as floor, and it acts like a dipole because of reflections. When utilizing the virtual ground, the transmission channel is further consistent because it limits the occurrence of reflection and bad electromagnetic waves perturbation.

Initially, the code was examined under the TOSSIM environment [35] (a simulation environment to experiment TinyOS programs), and after an extensive testing, programs were compiled and deployed on the Mica2 motes. To collect the experimental data we modified the existing Surge application [36] to include the desired parameters to be shown on the GUI. The Surge application is basically a simple example of a WSN multihop routing. Surge takes sensor readings and sends them towards the base-station (ID=0). Accompanying this application is a Java program that can be used to visualize the logical network topology and the sensor readings. Main features of the Surge application includes the detection of the existence of all the motes in WSN, displays mote information; including the mote ID (Identification Number), the number of messages sent from each mote and displays the topology of network. Surge after modification can be used for both WSN and MWSN. The Surge features are enhanced, e.g. it also shows the number of mobile messages received by the static motes from the mobile mote. Hence, the impact of adding mobility to a WSN can now be viewed considerably. In order to retrieve the data, the base-station was linked with the computer through the serial port using MIB510 programming board. We used ID=10 for the mobile mote. A tiny packet generator was developed to send messages at regular intervals to the static motes (motes with IDs other than 0 and 10). The remaining 6 motes (static motes) are programmed in such a way that they show the number of messages received by the mobile mote to the base station using a default multihop routing protocol [37] in TinyOS. The results were observed by the number of messages received by the static motes from the mobile mote. Several experiments have been performed in order to assess the reliability by observing the message loss. The performance is measured in terms of total number of messages successfully transferred against the total number of messages successfully received by the static sensor motes. Duty cycle for static motes is achieved by putting the CC1000 radio [38] in different modes of sleep periods. The antenna of MICA2 is a standard one-quarter wavelength monopole antenna and its radiation pattern does not exhibit a perfect sphere and it represents the dipole antenna model as in [39-40].

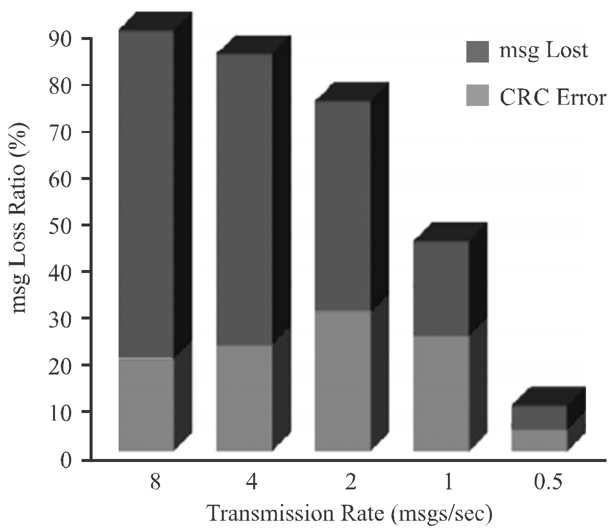
To ensure that the messages are successfully transferred from mobile mote to static motes, the timer rate was adjusted precisely to avoid any unwanted losses. Initial experiments are carried indoor using static scenario where two motes are taken into account. One static mote with ID=1 was placed at a distance of 5m from the base-station (ID=0), whereas the mobile mote (ID=10) was placed at a distance of 10m from the static mote. 20 mobile messages from mobile mote to static mote at different mobile timer rates, starting from 8-0.5msgs/sec, are sent. In order to send readings to the base station, the timer rate for the static motes remains constant, i.e., 0.5msgs/sec. It should be noted that for this scenario the static motes were always awake, i.e. 100% duty cycle. The achieved reliability is shown in Fig. 1(a) and it is analyzed that the maximum achieved reliability is 90% at the message timer rate equal to or less than 0.5msgs/sec. From Fig. 1(b) it is further analyzed that the majority of the messages are lost completely and very few are received at destination with CRC (Cyclic Redundancy Check) errors. For all experiments the Tiny OS parameter values are summarized in Table 1.

3.2 Experimental Environment

All experiments have been conducted at the Department of Telecommunication Engineering, Mehran University of Engineering & Technology, Jamshoro, Pakistan. Indoor experiments have been performed inside the corridors of the department so as to create a sub-urban scenario (because during the tests students pass across the sensor nodes). For outdoor experiments the parking area has been used in order to create a realistic urban scenario (because during the tests cars and students pass across the sensor nodes). For indoor and outdoor scenarios the reliability is assessed by initially keeping the mobile mote static (0 m/s) and then moving at various pedestrian speeds (from normal walk -0.625 m/s - to speedy walk -2.5 m/s).



(a) RELIABILITY VERSUS TRANSMISSION RATE



(b) MESSAGE LOSS RATIO VERSUS TRANSMISSION RATE

FIG. 1. MESSAGE DELIVERY STATISTICS FOR VARIOUS DATA RATES

TABLE 1. PARAMETER VALUES USED FOR MICA2 MOTES

Frequency	916MHz
Channel	Default (26)
Output Power	5dBm (0xFF)
Duty Cycle	100, 35.5, 7.53, and 1%
Antenna Position	Vertical (Back to Back)

Algorithms 1-3 describe our approach for accessing the reliability for duty cycled mobile WSNs

```
Algorithm-1: For Mobile Mote
1   counter ¬ 0;
2   INTERVAL ¬ 0.5 sec;
3   if Timer(INTERVAL) triggered then
4   if (ID == MOBILE ID) and (counter < 20) then
5   BROADCAST mobile message();
6   call Leds.greenOn(); //signals that we are sending a new message
7   counter++;
8   call Leds.greenOff(); //signals that we sent a new message
9   end
10  end
11  GOTO 3;

Algorithm-2. For Static Motes
1   if (mote awake() == TRUE) then
2   if (ID ¹ = MOBILE ID) and (ID ¹ = BASE STATION) then
3   RECEIVE mobile message();
4   call Leds.redOn(); //signals that we are receiving a new message
5   counter++;
6   send to BaseStation(counter);
    //send number of mobile messages received to mote ID=0
7   call Leds.redOff(); //signals that we received a new message
8   end
9   end

Algorithm-3: For Base Station Mote
1   if (ID == BASE STATION) then
2   receive keep alive(ID);
    //to maintain the routes from static motes to base station
3   receive(counter(ID));
    //Number of mobile message received by the static mote
4   show(counter(ID)); //on topology visualizer
5   end
```

Fig. 2(a) shows the indoor scenario, where 6 static motes with unique IDs are placed at a distance of 5m from each another at the virtual ground system. One base-station mote ID=0 is placed inside the Project Lab to capture the overall performance of mobile and static nodes. Mobile mote's initial position is set near to mote ID=1. Fig. 2(b) depicts the outdoor scenario with 6 static motes with unique IDs placed at a distance of 10m from one another in the parking area. The static motes with ID=4 and 6 were placed on the roof of the cars while others were placed on the virtual ground system. The base-station is also placed on the roof of a car. The mobile mote moves in a circular fashion starting from mote ID=1.

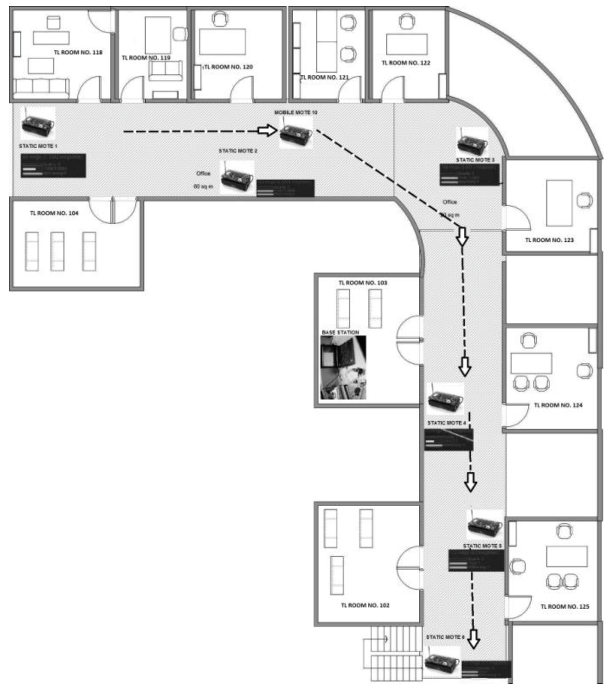
4. RESULTS

This section comprises of the results observed from various experiments based on different indoor and outdoor scenarios.

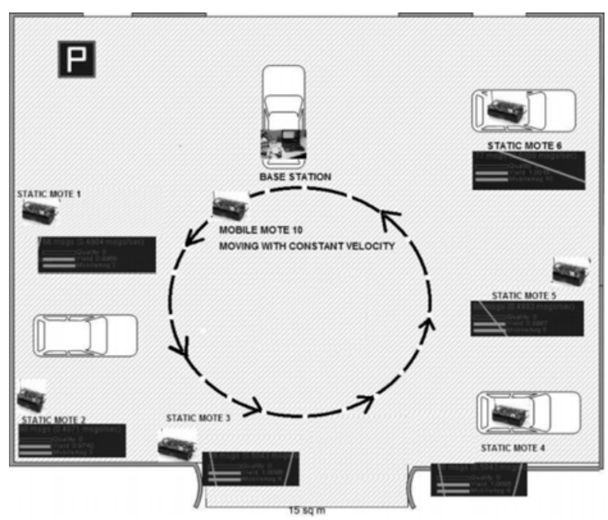
4.1 Indoor Scenario

Initially, the mobile mote with ID=10 is placed in between mote ID=3 and mote ID=4 in static position. After the setup, 20 mobile messages were sent from mobile mote to static motes with a constant rate of 0.5msgs/sec. It is analyzed from the results shown in Fig. 3(a), that the static mote ID=3 gets 19 messages and static mote ID=4 gets 17 messages out of 20 messages sent from mobile mote resulting in 95 and 85% reliability respectively. The reason behind this is that when the mobile mote is in static position only the motes near to it will receive messages and due to the presence of obstacles like walls and ground reflections, the other motes are unable to receive the messages from mobile mote. We also observe that due to duty cycling the reliability decreases gradually. This is because in generic conditions there is no synchronization between sending messages from the mote and the waking up of the static motes.

Fig. 3(b) shows the analysis where the mobile mote ID=10 is moving with a constant speed from static mote ID=1 to static mote ID=6. Again 20 messages were sent from the mobile mote to the static mote with a constant rate of 0.5msgs/sec.



(a) INDOOR SCENARIO: GROUND FLOOR CORRIDOR OF TELECOMMUNICATION



(b) OUTDOOR SCENARIO: PARKING AREA OF TELECOMMUNICATION

FIG. 2. EXPERIMENTAL SCENARIOS

It is analyzed that the static mote 1, 2, 3, 4, 5, and 6 achieve 20, 40, 25, 65, 15, and 55% reliability respectively at 0.625 m/s. It is observed that as soon as the mobile mote gets closer to the static mote, the static motes receives the mobile messages but still mote ID=4 and ID=6 gets more reliability than the others. This is because of the presence of students observed around the other nodes because of their lab schedules leading to decreased reliability. In order to achieve reliability the deployment of the network (indoor) must be done at some height from the ground and the static motes should be placed in such a way to avoid obstructions and reflections. Similar trends were observed at different mobility speeds. Furthermore, it is also observed that as the speed of mobile mote increases, the reliability tends to decrease compared to achieve reliability at lower speeds. This is generally because of less contact time with the static motes.

Fig. 3(c) depicts the reliability achieved with mobile mote interacting with static motes at different duty cycles. It is observed that as the duty cycling periods are increased there is a rapid decrease in the achieved reliability. Furthermore, due to mobility also the achieved reliability is decreased due to factors discussed above.

4.2 Outdoor Scenario

After the setup as depicted in Fig. 2(b), 20 mobile messages were sent from mobile mote to the static motes with a constant rate of 0.5 msgs/sec. Fig. 4(a) shows that the static mote ID=4 achieves up to 95% reliability while the static mote ID=6 achieves 40% reliability. The other motes did not receive any messages sent by the mobile mote, because the motes ID=4 and ID=6 were placed on the car's roof, i.e. at some height from the ground and also the mobile mote was placed at 5m above the ground while the other motes were placed on the ground. This is the reason that they were not able to receive any mobile messages. Also, for duty cycled static sensor motes we observe

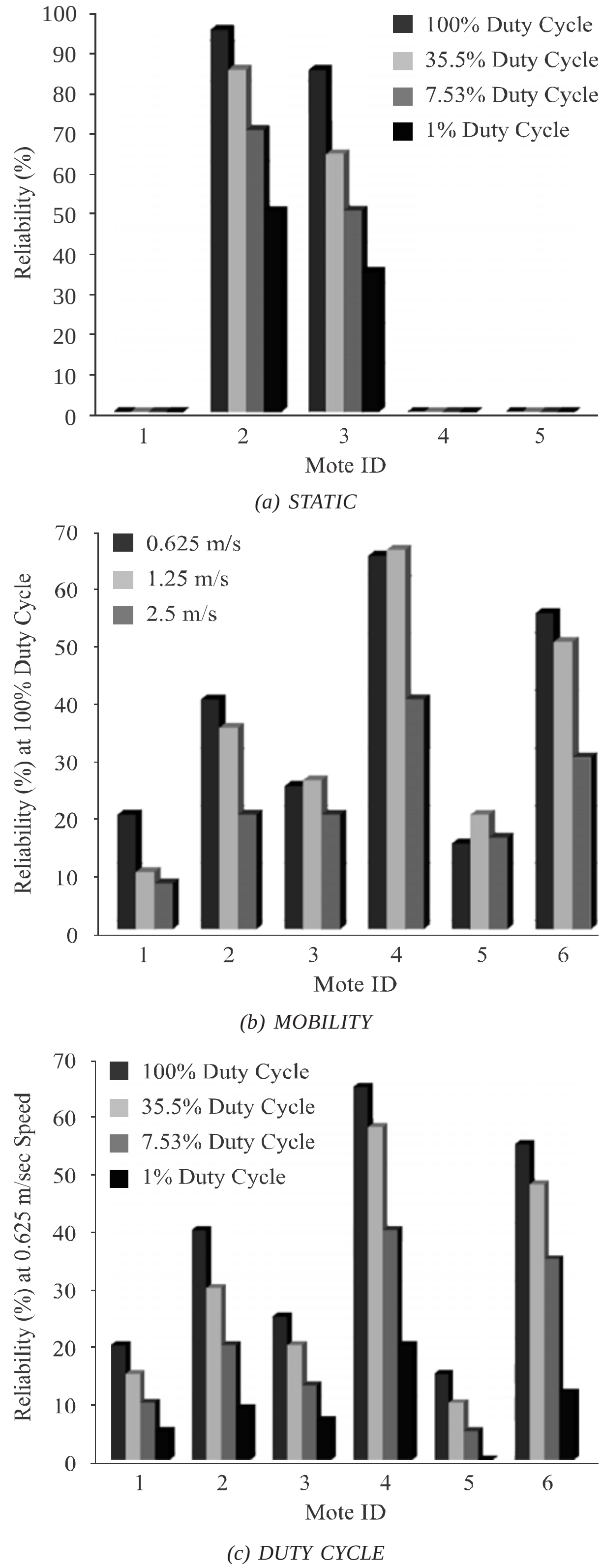


FIG. 3. INDOOR SCENARIO

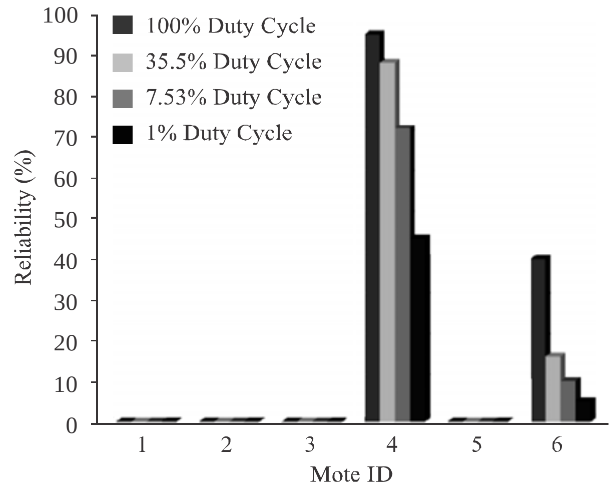
similar effect of indoor scenario where the reliability decreases with the increasing duty cycle periods of the motes.

Fig. 4(b) shows the analysis where the mobile mote ID=10 is moved with a constant speed from static mote ID=1 to the static mote ID=6. Again 20 mobile messages were sent from the mobile mote to static motes at a constant rate of 0.5 msgs/sec. It is observed that the static mote 1, 2, 3, 4, 5, and 6 achieve 10,15, 20, 60, 25, and 50% reliability at 1.25 m/s. It is again observed that static motes ID=4 and ID=6 are the most reliable of all because these motes were placed on the cars, i.e., on some height from the ground. Apart from this the mobile mote was also moved on some height above from the ground while the other motes were placed on the virtual ground and hence they were receiving less number of mobile messages. Similar effect can be observed at different speeds of the mobile mote.

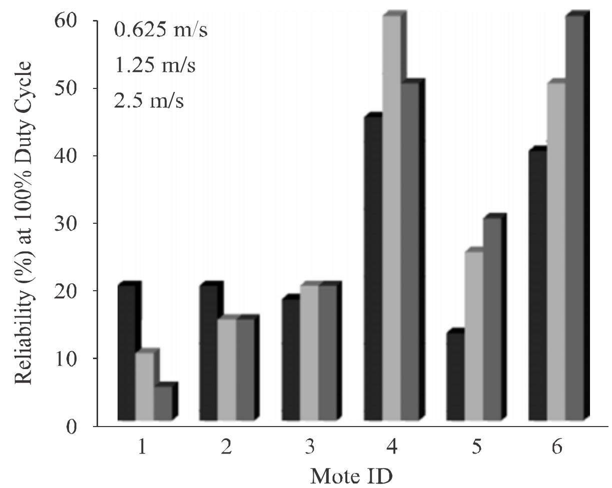
Fig. 4(c) depicts the effect of duty cycling on the mobility of the mote. Generally, it is observed that as the duty cycle of the static mote is increased the reliability is decreased exponentially. At very low duty cycle we observe that the reliability is very much decreased suggesting that the default broadcasting mechanism at regular intervals is very less reliable for message transmissions.

4.3 Data Transfer Reliability Improvement

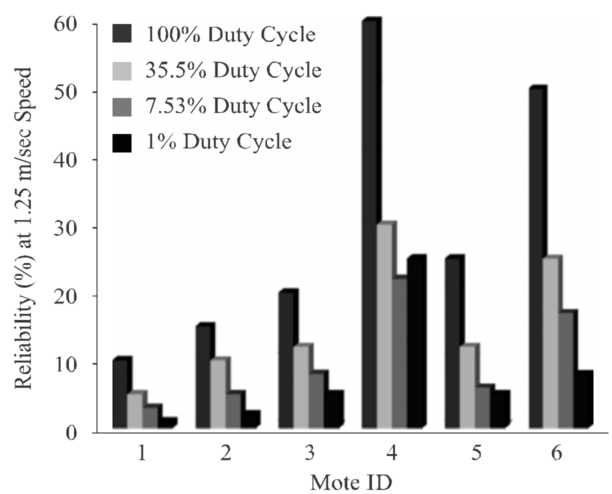
From the results discussed above there are many areas where the data transfer reliability can be improved. In order to improve the reliability the static nodes must know when the mobile node comes into contact for data transfer. Along with this some mobility aware ACK (Acknowledgment) mechanisms should be adapted to improve the message transfer reliability. To further improve the reliability the duty cycles should be adapted according to the data transfer rate. Also, the duty cycling according to the mobility pattern will also enhance the reliability.



(a) STATIC



(b) MOBILITY



(c) DUTY CYCLE

FIG. 4. OUTDOOR SCENARIO

5. CONCLUSION

The main objective of this paper is to assess how reliably the mobile mote transfers data when it is moving at various speeds along with the duty cycling of the static motes in the network. Overall we observe that due to mobility and duty cycling there is a loss of packets and 100% reliability is not achieved by periodic broadcasting of the messages. We observe that reliability is bit higher in indoor scenario compared to that of outdoor scenario. There is need to carefully adopt the appropriate acknowledgment mechanisms in order to retrieve the lost messages and increase the reliability. Furthermore, in order to utilize the duty cycling in order to save energy there should be tight integration between the movement of the mobile mote and the sleep schedules of the static sensor motes.

ACKNOWLEDGEMENTS

Authors would like to thank MS Rabail Kazi, for initial experiments and MS Nafeesa Zaki, for the improvement of the manuscript. This research was partially supported by Mehran University of Engineering & Technology, Jamshoro, Pakistan and National ICT R&D Fund, Ministry of Information Technology, Pakistan, under National Grassroots ICT Research Initiative.

REFERENCES

[1] Khelil, A., and Shaikh, F.K., Ali, A., and Suri, N., "gMAP: an Efficient Construction of Global Maps for Mobility-Assisted Wireless Sensor Networks", Proceedings of the Conference on Wireless On Demand Network Systems and Services, pp. 189-196, 2009.

[2] Hill, J.L., “System Architecture for Wireless Sensor Networks”, Ph.D. Thesis, University of California, Berkeley, California, United States, 2003.

[3] Kuorilehto, M., H¨annik¨ainen, M., and H¨am¨al¨ainen, T.D., "A Survey of Application Distribution in Wireless Sensor Networks", EURASIP Journal Wireless Communication Network, No. 5, pp. 774-788, 2005.

[4] Yan, T., “Analysis Approaches for Predicting Performance of Wireless Sensor Networks”, Ph.D. Thesis, University of Virginia, 2004.

[5] Zhang, H., Arora, A., Choi, Y., and Gouda, M.G., "Reliable Bursty Convergecast in Wireless Sensor Networks", International Symposium on Mobile Ad Hoc Networking and Computing (MobiHoc), pp. 266-276, 2005.

[6] Shaikh, F.K., Khelil, A., Ayari, B., Szczytowski, P., and Suri, N., "Generic Information Transport for Wireless Sensor Networks", IEEE International Conference on Sensor Networks, Ubiquitous, and Trustworthy Computing, pp. 27-34, 2010.

[7] Ahn, G.S., Hong, S.G., Miluzzo, E., Campbell, A.T., and Cuomo, F., "Funneling-MAC: A Localized, Sink-Oriented MAC for Boosting Fidelity in Sensor Networks", Proceedings of 4th International Conference on Embedded Networked Sensor Systems, pp. 293-306, ACM, 2006.

[8] Wan, C.Y., Eisenman, S.B., Campbell, A.T., and Crowcroft, J., "Siphon: Overload Traffic Management Using Multi-Radio Virtual Sinks in Sensor Networks," Proceedings of 3rd International Conference on Embedded Networked Sensor Systems, pp. 116-129, ACM, 2005.

[9] Liu, Z., Wei, C., Ma, Y., Li, H., Niu, X., and Wang, L., "UCOR: An Unequally Clustering-Based Hierarchical Opportunistic Routing Protocol for WSNs", Wireless Algorithms, Systems, and Applications, pp. 175-185, Springer, 2013.

[10] DiFrancesco, M., Das, S., and Anastasi, G., "Data Collection in Wireless Sensor Networks with Mobile Elements: A Survey", ACM Transactions on Sensor Networks, 2011.

[11] Restuccia, F., Anastasi, G., Conti, M., and Das, S., "Analysis and Optimization of a Protocol for Mobile Element Discovery in Sensor Networks", IEEE Transactions on Mobile Computing, 2013.

[12] Artemios, V., "A Survey of Delay and Disruption-Tolerant Networking Applications", Journal of Internet Engineering, Volume 5, No. 1, pp. 331-344, 2012.

[13] Borgia, E., Anastasi, G., and Conti, M., "Energy Efficient and Reliable Data Delivery in Urban Sensing Applications: A Performance Analysis", Computer Networks, 2013.

[14] Liu, T., Sadler, C., Zhang, P., and Martonosi, M., "Implementing Software on Resource-Constrained Mobile Sensors: Experiences with Impala and Zebranet", Proceedings of 2nd International Conference on Mobile Systems, Applications, and Services, pp. 256-269, 2004.

[15] Link, J.A.B., Wehrle, K., Osechas, O., and Thiele, J., "Ratpack: Communication in a Sparse Dynamic Network", ACM SIGCOMM, 2008.

[16] Sankarasubramaniam,Y., Akan, O.B., and Akyildiz, I.F., "Esrt: Event-to-Sink Reliable Transport in Wireless Sensor Networks", Interational Symposium on Mobile Ad Hoc Networking and Computing (MobiHoc), 2003.

[17] Stann, F., and HeIdemann, J., "RMST: Reliable Data Transport in Sensor Networks", International Workshop on Sensor Network Protocols and Applications, pp. 102-112, 2003.

[18] Stathopoulos, T., HeIdemann, J., and Estrin, D., "A Remote Code Update Mechanism for Wireless Sensor Networks", Technical Report Cens-tr-30, University of California, Los Angeles, 2003.

[19] Texan, N., Cayirci, E., and Caglayan, M.U., "End-to-End Reliable Event Transfer in Wireless Sensor Networks", Personal Indoor and Mobile Radio Communications, Volume 2, pp. 989-994, 2004.

[20] Wang, C., Daneshmand, M., Li, B., and Sohraby, K., "A Survey of Transport Protocols for Wireless Sensor Networks", IEEE Network Magazine, 2006.

[21] Zhang, H., Arora, A., Choi, Y., and Gouda, M.G., "Reliable Bursty Convergecast in Wireless Sensor Networks", Interational Symposium on Mobile Ad Hoc Networking and Computing (MobiHoc), pp. 266-276, 2005.

[22] Zhou, Y., and Lyu, M.R., "Port: A Price-Oriented Reliable Transport Protocol for Wireless Sensor Networks", International Symposium on Software Reliability Engineering, pp. 117-126, 2006.

[23] Anastasi, G., Conti, M., and Francesco, D., "An Analytical Study of Reliable and Energy-Efficient Data Collection in Sparse Sensor Networks with Mobile Elements", Proceedings of EWSN, 2006.

[24] Olof, R., Frederik, H., Per, G., and Lars-ke, L., "Repeatable Experiments with Mobile Nodes in a Relocatable WSN Testbed", 1st International Workshop on Mobility in Wireless Sensor Networks, 2010.

[25] Anastasi, G., Conti, M., and DiFrancesco, M., "Reliable and Energy-Efficient Data Collection in Sparse Sensor Networks with Mobile Elements", Performance Evaluation, Volume 66, No. 12, pp. 791-810, 2009.

[26] Zhao, W., Ammar, M., and Zegura, E., "A Message Ferrying Approach for Data Delivery in Sparse Mobile Ad Hoc Networks",Proceedings of 5th ACM International Symposium on Mobile Ad Hoc Networking and Computing, pp. 187-198, 2004.

[27] Navid, H., Olaf, L., Frederik, H., Olof, R., and Thiemo, V., "Efficient Mobile Data Collection with Mobile Collect", 8th IEEE International Conference on Distributed Computing in Sensor Systems, 2012.

[28] Shaikh, F.K., and Zeadally, S., and Siddiqui, F., "Energy Efficient Routing in Wireless Sensor Networks", Springer, pp. 131-157 London, 2013.

[29] Keshavarzian, A., Lee, H., and Venkatraman, L., "Wakeup Scheduling in Wireless Sensor Networks", Proceedings of 7th ACM International Symposium on Mobile Ad Hoc Networking and Computing, pp. 322-333, 2006.

[30] Anastasi, G., Conti, M., DiFrancesco, M., and Passarella, A., "An Adaptive and Low-Latency Power Management Protocol for Wireless Sensor Networks", ACM International Workshop on Mobility Management and Wireless Access, pp. 67-74, 2006.

[31] Paruchuri, V., Basavaraju, S., Durresi, A., Kannan, R., and Iyengar, S.S., "Random Asynchronous Wakeup Protocol for Sensor Networks", International Conference on Broadband Networks, pp. 710-717, 2004.

[32] Zheng, R., Hou, J.C., and Sha, L., "Asynchronous Wakeup for Ad Hoc Networks", International Symposium on Mobile Ad Hoc Networking & Computing, pp. 35-45, 2003.

[33] Crossbow Technology Inc., "TinyOS Getting Started Guide", 2003.

[34] Anastasi, G., Falchi, A., Passarella, A., Conti, M., and Gregori, E., "Performance Measurements of Motes Sensor Networks", Proceedings of 7th ACM International Symposium on Modeling, Analysis and Simulation of Wireless and Mobile Systems, pp. 174-181, October, 2004.

[35] Levis, P., Lee, N., Welsh, M., and Culle, D., "Tossim: Accurate and Scalable Simulation of Entire Tinyos Applications", Proceedings of 1st ACM Conference on Embedded Networked Sensor Systems, Los Angeles, CA, USA, 2003.

[36] "Surge Application", http://www.tinyos.net/tinyos-1.x/apps/Surge/ (Last Accessed: 21-10-2013).

[37] "Multihoprouter Protocol", http://webs.cs.berkeley.edu/tos/tinyos-1.x/doc/multihop/multihop_routing.html (Last Accessed: 21-10-2013)

[38] "Cc1000 radio." http://www.tinyos.net/tinyos-1.x/doc/mica2radio/CC1000.html (last accessed: 22-10-2013)

[39] Silva, A.R., and Vuran, M.C., "Empirical Evaluation of Wireless Underground-to-Underground Communication in Wireless Underground Sensor Networks", Distributed Computing in Sensor Systems, pp. 231-244, Springer, 2009.

[40] Scott, T., "Mica Mote Antenna Radiation Pattern Analysis", Master's Thesis, University of Victoria, May, 2004.