Mobile Robot Tracking in Wireless Sensor Networks

Yoon Kah Leow and Ying Shang

Abstract— **This paper studies the mobile robot tracking problem in a wireless sensor network consisting of several sensor nodes collecting sensor information and transmitting data packets in order to determine a mobile robot's location at real-time. This paper proposed an intrusion detection algorithm based on collecting light signal and a counter-based routing protocol integrated with Automatic Repeat reQuest (ARQ). The counter-based routing protocol makes use of a randomized delay before a data transmission to reduce data redundancy. This provides a lightweight solution while preserving the advantage of being an easily implementable protocol. Furthermore, an event-based interface to facilitate handshaking between the new routing protocol and the proposed lightweight motion detection algorithm is defined to realize the intrusion detection application. The detection algorithm and the routing protocol are implemented in a prototypical wireless sensor network using MICA2 sensor motes.**

I. Introduction

Mobile robot tracking [1] has many real-world applications, such as search and rescue operations, military surveillance, and the tracking of moving targets in industrial warehouses. The essence of the mobile tracking problem is to accurately locate the moving targets. However, it is often in the case of a practical situation whereby human intervention is not desirable in the mobile tracking. With great advances in the realms of micro-electromagnetic systems (MEMS), technology has rendered wireless sensor networks [2, 10] a viable solution suitable for the mobile tracking problem with limited human intervention.

A wireless sensor network consists of spatially distributed embedded devices that are capable of acting autonomously yet collaborating among each other in order to achieve a common goal. These devices are well-known for their self-configurable nature, and they provide a high level of automation that can often replace some levels of human roles. By collaborating with a wireless sensor network in the mobile tracking problem, it allows users to gain global visibility of the pursuit grounds even without visual contact of the moving target. For instance, in Fig. 1, the pursuer vehicles have limited visibility without the wireless sensor network. On the other hand, in Fig. 2, with the wireless sensor network, the pursuers are able to gain information of the terrain nature and the evader's location.

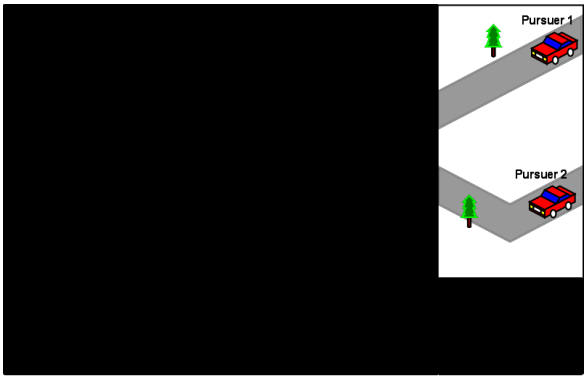

Fig. 1: Pursuer visibility - Without the sensor network.

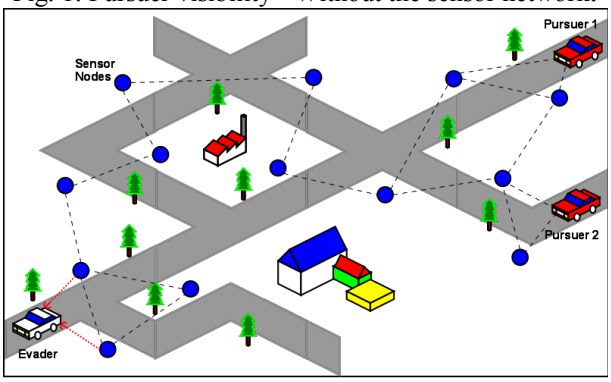

Fig. 2: Pursuer visibility- with the sensor network.

In this paper, a time and energy efficient motion detection algorithm is designed. A new routing protocol is proposed to by making use of a randomized delay before a data transmission to reduce redundancy. This provides a lightweight solution while preserving the advantage of being an easily implementable protocol. ARQ is utilized to address the problem of virtual network partition while achieving a light-weight routing protocol. Furthermore, an event-based interface to facilitate handshaking between the new routing protocol and the proposed lightweight motion detection algorithm is also defined to realize the intrusion detection application. The intrusion detection algorithm and the routing protocol are implemented in a prototypical wireless sensor network consisting of four MICA2 sensor motes from Crossbow Technology [3]. These sensors are pre-programmed with the application software built over the TinyOS operating system, and they perform the tracking algorithm based on the detection of light signals and route data packets across the ad-hoc wireless sensor network. In order to facilitate testing and simulations, an iRobot® Create

This work was supported by the Southern Illinois University Edwardsville Graduate School Funded University Research under Grant 2-79433.

Yoon Kah Leow is with the Department of Electrical & Computer Engineering, The University of Arizona, Tucson, AZ 85721, USA, (e-mail: yleow@email.arizona.edu).

Ying Shang, corresponding author, is with the Department of Electrical and Computer Engineering, Southern Illinois University Edwardsville, IL 62026, USA (e-mail: yshang@siue.edu).

robot [7] is used to act as the moving target in the sensor network. The end result is that the sensor network is able to discover the moving robot's location and relay this information back to the users.

II. Intrusion Detection and Routing Protocol

In order to provide a complete solution to the mobile tracking problem, the research procedure is broken down into the intrusion detection mechanism design and the data routing protocol design.

A. Intrusion Detection Mechanism

In the mobile tracking, sensor motes need to be able to detect intruders in the region. The challenge is the versatility for the sensors to differentiate between a positive and a negative detection. Moreover, in a realistic situation, it is very likely that a sensor network will be deployed over a long period of time. The sensor needs to realize the ever-changing surrounding environment, such as light ambience and background noise, and adapt itself constantly in order to provide accurate detections.

This paper focuses on the intrusion detection [5, 11] that is based on the changes of the light signals. On one hand, in order to handle changing light ambience in the environment, the desired motion detection algorithm needs to tune itself to the background light ambience constantly. On the other hand, it is a requirement for the sensors to be deployed for a long period of time without any human intervention. Hence, the algorithm needs to be able to perform the fine-tuning process autonomously.

The light sensor is programmed to acquire light values at two frequencies 10 Hz and 0.67 Hz. The two frequencies are selected based on experimental calibrations after running exhaustive tests with a robot moving at a fixed velocity. In order to take care of energy constraints on these embedded devices, the faster frequency of 10 Hz is only used when a large difference in light ambience has been observed, that is, a motion is suspected within the sensor's sensing range. Hence, the motion detection algorithm will sense light values based on the slower 0.67 Hz while operating under normal light ambience conditions.

During the intrusion detection, a light value that is just retrieved will be compared with the previously retrieved light value. A motion is suspected if the difference between them is more than 1.0 count. If a motion is suspected, the algorithm will increase the light sampling frequency to 10 Hz and a second set of light value will be retrieved. Hence, this second set of light value will replace the current light value and will be compared with the previous set of the light value. Positive motion detection will be reported if there are two consecutive differences in the light ambience that is more than 1.0 count. By buffering the light values, this gives allowance for slight changes in the light ambience throughout the monitoring process to achieve a fine-tuning effect. Hence, the sensors can be deployed in the field without any further calibrations as the light ambience changes over a long period of time. The flowchart in Fig. 3 illustrates the motion detection algorithm.

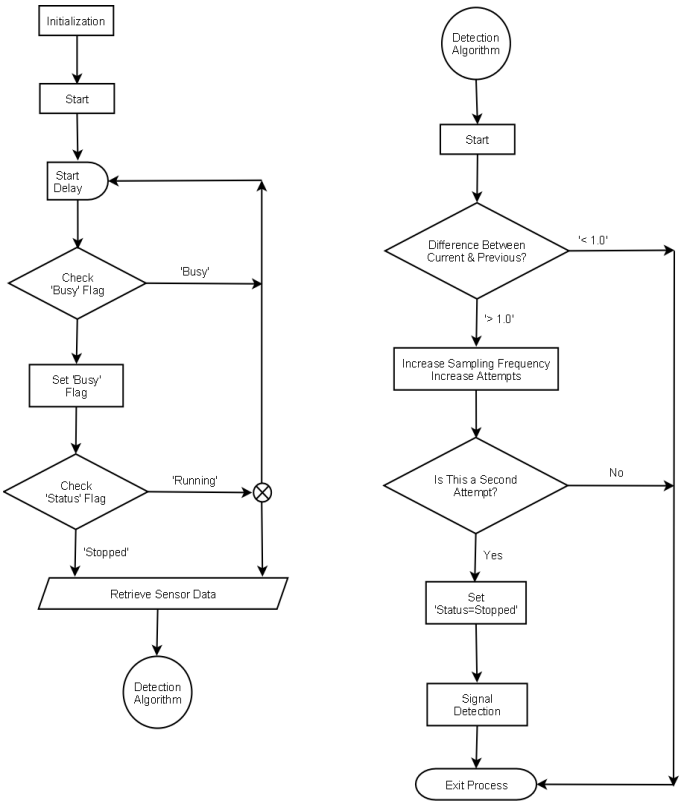

Fig. 3: Motion detection algorithm flowchart.

B. Counter-Based (CB) Routing Protocol

After the intrusion detection has taken place, the sensor which initiates the detection needs to convey the message to the surrounding sensors while the surrounding sensors need to propagate the message throughout the entire sensor network until the user is informed of the detection. Hence, an efficient routing protocol [4, 6, 9, 12, 13] needs to be devised.

Wireless sensor network applications can be classified into the following four types of data flow: event-driven, query-driven, continuous, and hybrid [8]. Our research focuses on the event-driven application. One of the requirements of such an application is that, the event has to be reported to the data sink in a timely fashion, so that a corresponding action can be carried out. Hence, it is desirable for the data to travel via the shortest path to minimize the propagation delay. Furthermore, a reliable propagation path is essential to ensure a high Quality of Service (QoS) during the data delivery. In order to minimize the power wastage, a counter-based (CB) routing protocol is utilized [8]. A pure flooding-based broadcasting protocol is modified by inserting a randomized delay before transmitting a data packet. Each sensor node retains a copy of the last routed packet.

Fig. 4 illustrates the CB routing protocol. Assuming that only node A and B are within communication range of the sender. The sender has to route a data packet via node A or node B in order to reach node C. Hence, by introducing a random delay before each transmission, nodes A and B will transmit the relayed data packet at a different time depending on which random timer expires first. Therefore, if node A transmits first and intercepts node B before transmission, this will prevent a redundant data transmission as node B will detect data duplication and drops the packet silently thereby saving transmission power and reducing network traffic.

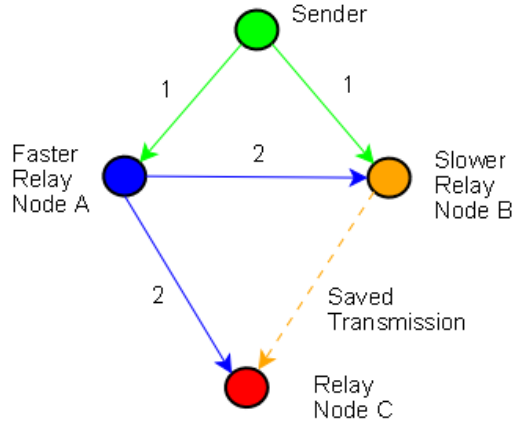

Fig. 4: Routing the same packet via the same sensor node.

C. Automatic Repeat reQuest (ARQ) in Counter-Based Routing Protocol

The CB routing protocol is especially advantageous in a network deployment that has at least 3-connectivity. However, due to its broadcasting nature, one disadvantage is lack of feedback from a receiving node to ensure QoS. Furthermore, in a practical scenario, the network deployment is often randomly deployed with a network model that closely approximates a Poisson distribution leading to deployments that are 2-connectivity or 1-connectivity. Due to the in-deterministic nature of the sensor locations, a CB routing algorithm might result in a network partition despite that sensors are within the communication range. In this paper, we refer to this problem as a virtual network partition (VNP).

Fig. 5 illustrates a randomly deployed sensor network that will create a potential VNP. Two clusters are realized based on the deployment. Thereafter, the left cluster can relay data packets to the data sink only via the critical node situated between the two clusters. As all the nodes in a cluster are within communication range, the other two receiving sensors will receive the data packet from the transmitting sensor (i.e., source). Based on the CB routing protocol, both sensors will attempt to relay the same data packet at a different time. Assuming the sensor node connected to the critical node is the slower one. Hence, the faster node will intercept the slower node and cause it to drop the data packet even before the packet is relayed. Hence, the message will be lost even though the sensors are fully connected.

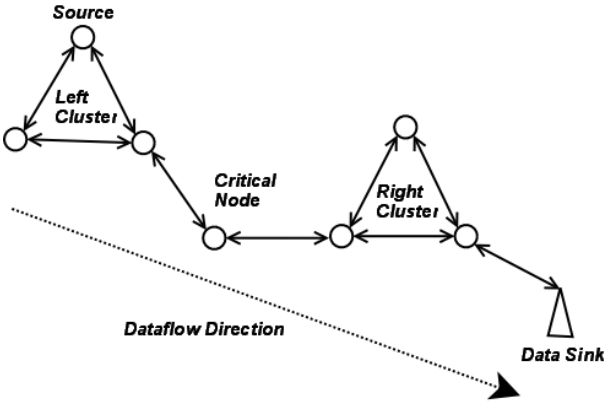

Fig. 5: Virtual network partition.

In order to address the problem of packet loss, Automatic Repeat reQuest (ARQ) is integrated into the CB routing protocol. By virtue of a broadcasting based protocol, each receiving sensor node is responsible for broadcasting a relayed data packet after a random delay. Hence, if a pair of sender and receiver sensors is within the communication range, the sender should expect to receive the same packet from the receiver after a maximum delay. This maximum delay is equivalent to the summation of the maximum random delay, time taken to transmit the data packet, and the round-trip propagation delay. Therefore, the sender will wait for a reply in the form of a transmitted data packet based on the period defined by maximum delay.

The ARQ timer is reset when the sender receives any packet from its neighboring sensors. Hence, a sender will retransmit the previously routed data packet if it does not receive any data packets after an ARQ timeout period of maximum delay. In order to solve the virtual network partition problem, an extra data field, *override*, is also introduced into the sensor data payload. The override field instructs the receiver mote to allow the retransmitted data packet to be relayed even though it is a duplicated packet. However, the receiving node will reset the override field before the data packet is relayed. This will ensure that the data packet is only overridden for the first layer of sensor motes with respect to the node where it is first set. The pseudo-code in Fig. 6 and the flowchart in Fig. 7 illustrate the routing protocol.

To the best of our knowledge, this work is an early attempt to integrate ARQ into a CB routing protocol to address the problem of VNP. Furthermore, an event-based interface to facilitate handshaking between the new routing protocol and the proposed lightweight motion detection algorithm is also defined to realize the intrusion detection application.

```
DataMsg* current_pkt;
int prev_hop_count;

Function Receive (DataMsg* data_pkt) {
  Resend_timer_stop();
  int hop_count = data_pkt->hop_count;

  if (data_pkt is duplicated) {
    if (hop_count => prev_hop_count) {
      if (override) {
        data_pkt->override = 0;
      }
      else {
         Send_timer_stop();
        return;
      }
    }
  }
  prev_hop_count = data_pkt->hop_count;
  data_pkt->hop_count++;
  current_pkt = data_pkt;
  Send_timer_fire_once(random_delay);
}

Function Send_timer_fired() {
  Transmit(current_pkt);
  Resend_timer_fire_once(round_trip_delay);
}

Function Resend_timer_fired() {
  current_pkt->override = 1;
  Transmit(current_pkt);
}
```

Fig. 6: Routing protocol pseudo-code.

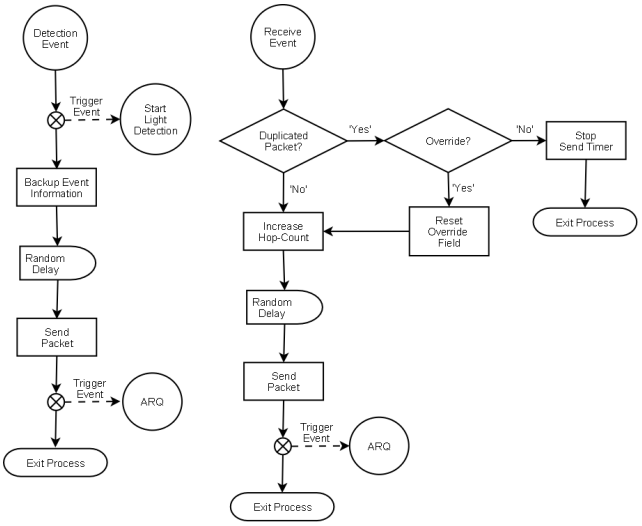

Fig. 7: Routing protocol flowchart.

III. HARDWARE IMPLEMENATION

The implementation of the mobile tracking in wireless sensor networks can be separated into four main portions: the motion detection system, the routing protocol, the path planning algorithm, and the system integration. The entire system requires collaborations between sensor hardware, robot hardware, and system software for both of the wireless sensors and the robot.

A. Experimental Hardware

The sensors that are used in the project are MICA2 sensors from Crossbow Technology [3], shown in Fig. 8. On the *MPR400CB*, the processor onboard is the *Atmel ATmega128L* micro-controller. It has 128KBytes of instruction *EEPROM* and another 4KBytes of data *EEPROM* for data storage. The communication module onboard is the *Chipcon CC1000* radio. It also has a 51 pin I/O connector to interface to the *MTS400CA* sensor board shown in Fig. 9. The hardware available for use on the sensor board are the humidity and temperature sensor, barometric pressure and temperature sensor, light sensor and 2-axis accelerometer [3]. This project makes use of the light sensor to implement the motion detection algorithm.

Fig. 8: MICA2 MPR400CB sensor mote [3].

Fig. 9: MTS400CA sensor board [3].

The implementation of the motion detection algorithm and the routing protocol are built over the TinyOS operating system. Experiments are carried out to analyze the efficiency of the algorithms with an objective to project an accurate simulation that is close to the actual mobile tracking problem. The system architecture of the experiment is shown in Fig. 10.

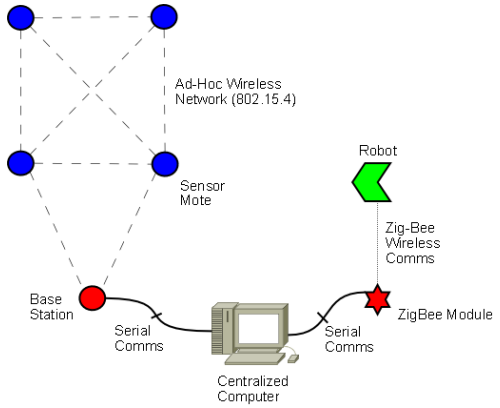

Fig. 10: System architecture.

A simple testbed is constructed to simulate a sensor field while a robot is utilized to simulate an intruder in the sensor field. Fig. 11 illustrates the "iRobot® Create" robot, used to simulate a moving robot in the sensor field. The robot provides an electronic and software interface called the iRobot® Create Open Interface for controlling Create's behavior and reading its sensors [7].

Fig. 11: "iRobot® Create" robot.

The red circle locates the 25-pin cargo bay connector in which the external controller can interface with. In this experiment, a ZigBee module is interfaced to this connector, so that the centralized computer is able to control the robot wirelessly. The main components on the interface circuit are listed and the connections on the breadboard are illustrated in Fig. 12.

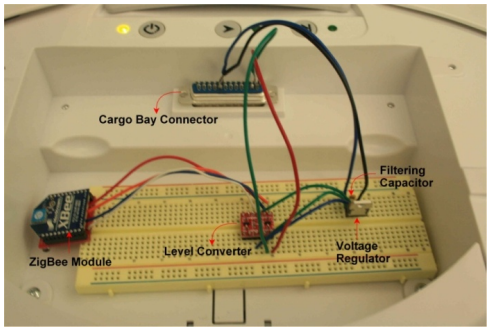

Fig. 12: Breadboard circuit mounted on iRobot® Create.

Fig. 13 illustrates the wireless sensors that are setup beneath the testbed. Each sensor is assigned with a unique node ID with node ID 1 dedicated to the base station. Due to the deployment strategy of the sensors, the testbed is divided into four cells which are identified by the corresponding wireless sensor's node ID found beneath it. Fig. 14 illustrates the four portions on the testbed with an iRobot® Create robot deployed over it.

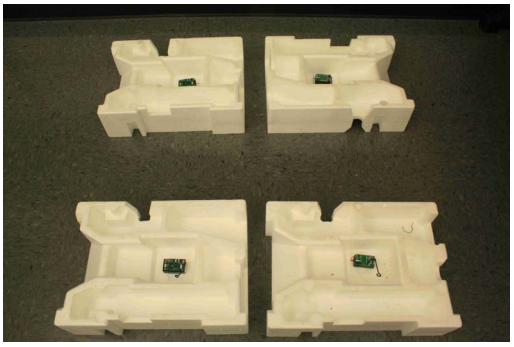

Fig. 13: Experiment testbed sensors.

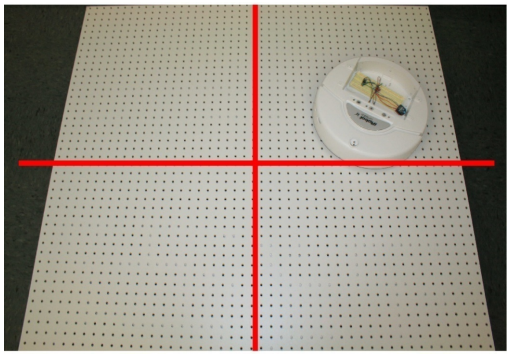

Fig. 14: Experiment testbed.

B. Experiment Observations

The light that passes through the surface holes illuminates the individual cells. Experiments are conducted under the normal room condition in which the light ambience within each cell is approximately 20 counts. As the robot travels across the sensor motes, the light ambience will drop gradually until a minimum value of approximately 3 counts. When the sensors report a positive detection based on the difference in light ambience, the horizontal distance from the position of the sensor to the point where the first drop of light ambience can be detected denotes the sensing range of a sensor. The nearest sensor node ID numbers to the moving robot are shown on the user's computer shown in Fig. 15. In all, the wireless sensor network is able to report the location of the robot promptly and accurately. The results justify the advantage of employing wireless sensor network in the mobile tracking problem.

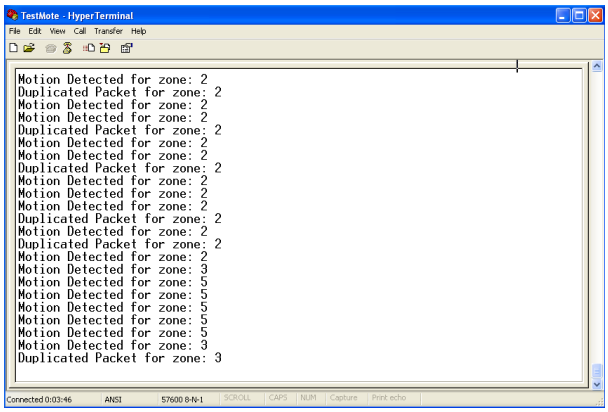

Fig. 15: The nearest sensor node IDs to the moving robot.

IV. CONCLUSION

This paper studies the mobile robot tracking problem, where users can discover the moving robot's location with the help of a wireless sensor network. Based on the available MICA2 sensor mote hardware, an energy and time efficient motion detection algorithm is designed and a new counter-based routing protocol is proposed by making use of automatic repeat request in solving the problem of virtual network partition. This provides a lightweight solution while preserving the advantage of being an easily implementable protocol. Both the intrusion detection algorithm and the routing protocol are implemented in a prototypical wireless sensor network consisting of four MICA2 sensor motes. Future research is to extend the motion detection algorithm and the routing protocol for intrusion detection with multiple robots.

REFERENCES

[1] B. Awerbuch and D. Peleg, , "Online tracking of mobile users," *Journal of the Association. for Comuting. Machinery*, 42, no. 5, pp. 1021–1058, 1995.

[2] A. Bar-Noy, I. Kessler, "Tracking mobile users in wireless networks, in *Proceedings of IEEE INFOCOM*, pp. 1232–1239, 1993.

[3] Crossbow Technology, "MTS/MDA Sensor Board Users Manual," http://www.xbow.com.

[4] T. van Dam and K. Langendoen, "An adaptive energy-efficient mac protocol for wireless sensor networks," in *Proceedings of the 1st International Conference on Embedded Networked Sensor Systems*, pp. 171-180, 2003.

[5] O. Dousse, C. Tavoularis, and P.Thiran, "Delay of intrusion detection in wireless sensor networks," in *Proceedings of the 7th ACM International Symposium on Mobile Ad Hoc Networking and Computing*, pp. 155-165, 2006.

[6] A. El-Hoiydi and J.-D. Decotignie., "Wisemac: An ultra low power mac protocol for multi-hop wireless sensor networks," *Algorithmic Aspects of Wireless Sensor Networks*, vol. 3121, pp. 18-31, 2004.

[7] iRobot® Create from iRobot Corporation. http://www.iRobot.com.

[8] S. Ni, Y. Tseng, Y. Chen and J. Sheu, "The broadcast storm problem in a mobile ad-hoc network," in *Proceedings of the 5th annual ACM/IEEE international conference on Mobile computing and networking*, pp. 151-162, 1999.

[9] J. Polastre, J. Hill, and D. Culler, "Versatile low power media access for wireless sensor networks," in *Proceedings of the 2nd International Conference on Embedded Networked Sensor Systems*, pp. 95-107, 2004.

[10] S. Tilak, N. Abu-Ghazaleh, and W. Heinzelman, "A taxonomy of wireless micro-sensor network models," *ACM SIGMOBILE Mobile Computing and Communications Review,* vol. 6, no. 2, pp. 28-36, 2002.

[11] Y. Wang, X. Wang, B. Xie, D. Wang, and D.P. Agrawal, "Intrusion detection in homogeneous and heterogeneous wireless sensor networks," in *IEEE Transactions on Mobile Computing*, vol. 7, no. 6, pp. 698-711, 2008.

[12] W.B. Heinselman, A.P. Chandrakasan, and H. Balakrishnan, "An application-specific protocol architecture for wireless microsensor networks," in *IEEE Transactions on Wireless Communications*, vol. 1, no. 4, pp. 660-670, 2002.

[13] W. Ye, J. Heidemann, and D. Estrin, "An energy-efficient MAC protocol for wireless sensor networks," in *Proceedings of the IEEE INFOCOM*, pp. 1567-1576, 2002.