# Sphere Mobile Robots for Highly Connected Wireless Multihop Sensor Networks

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***Abstract*—For wireless sensor networks with autonomously mobile sensor nodes, the sensor nodes are required to support both agile mobility and high connectivity. The agile mobility guarantees high observability and the high connectivity realizes high performance wireless multihop transmissions of sensor data. This paper proposes sphere mobile robots with sensor devices which moves any direction without the time overhead for change of mobility direction and with multiple directional antennas to detect mobility of neighbor mobile robots. Based on the change of direction and receipt power of wireless signals from the neighbor mobile robots, each mobile robots find its way to keep connectivity with the neighbor mobile robots. The constitution of the sphere mobile robots and the results of the brief performance evaluation experiments are also discussed.**

***Index Terms*—Wireless Sensor Networks, Sphere Robots, Directional Antennas, Wireless Multihop Networks.**

## I. INTRODUCTION

A Wireless multihop network consists of multiple wireless mobile nodes which move in accordance with application requirements or independently of them. Mobility strategy of mobile sensor nodes according to mobility of observed objects is proposed [8]. In [5], mobility of agricultural sensor nodes with solar battery power supply is discussed which is determined according to changes of sunny places effected by growth of crops. On the other hand, in order to exchange sensor data messages required for sensor network applications, higher connectivity among sensor nodes is required to be achieved and maintained. For example, in mobile robot networks supporting disaster rescue, construction sites, mine-clearing operations and so on, each mobile robot achieves sensor data to grasp environmental states, executes its application program and autonomously moves and works. In addition, it is required to exchange data messages containing sensor data and/or requests for mobility and working to the others among the mobile robots. Wireless multihop communication is one of the promised methods to provide high connectivity among mobile wireless nodes and is going to be applied to sensor networks [4]. Here, multiple mobile wireless nodes serves a role of intermediate node to support end-to-end connectivity by forwarding received messages. In order to configur a wireless multihop transmission route between geographically separated two wireless nodes, intermediate nodes are required to be at proper locations and the connectivity should be kept even with mobility of the intermediate nodes. In addition, though hop-by-hop wireless transmission quality is usually unstable due to distances between successive intermediate wireless nodes in a route and existence of obstacles and noise, end-to-end transmission qualities such as transmission delay, reachability and throughput of data messages which are required by applications should be satisfied Therefore, each mobile wireless nodes should rapidly move to a location which satisfie both requirements for observation quality requested by applications and communication quality. This paper proposes dedicated intermediate mobile wireless nodes which move for keeping high communication quality as intermediate nodes in wireless multihop transmission route between mobile robots moves autonomously based on their observation quality in mobile wireless robot network where the autonomously mobile robots are sparsely distributed. For achieving better improvement of communication quality by introduction of not so many dedicated intermediate nodes, it is required to determine its proper location and to move rapidly. Thus, this paper proposes and design sphere wireless robots and evaluates their performance. In addition, the methods to detect mobility of neighbor mobile wireless nodes and to determine its mobility autonomously are also discussed.

## II. RELATED WORKS

In order to realize a wireless multihop network, routing of data messages is critical and various ad-hoc routing protocols have been proposed [15]. It is assumed for these routing protocols that distribution of wireless nodes is enough dense to detect and maintain a wireless multihop transmission route from a source wireless node to a destination one with high probability. Even in case of route breakage caused by mobility or failure of an intermediate node, route repair and/or route re-detection work well and another route is surely configured In sensor networks, whole the observation area is covered by a set of observable ranges of wireless sensor nodes continuously and sensor data messages are transmitted from all the distributed sensor nodes to a sink node by highly dense distribution of the wireless sensor nodes. In addition, intentional distribution of the sensor nodes to achieve enough high connectivity, induction of mobility plans to keep connectivity even with mobility of wireless sensor nodes and sleep/wakeup scheduling methods to take a tradeoff between transmission delay and battery consumption are also discussed [11].

To maintain connectivity of a wireless multihop network even with low density distribution of mobile wireless nodes, a proper location of each mobile wireless node is determined by distances to its neighbor nodes [14]. Here, locations of wireless sensor nodes are dynamically changed based on an attraction and repulsion model to keep connectivity of the wireless network. In addition connectivity of the network is mobility of mobile wireless nodes based on the attraction and repulsion model and communication quality is controlled by properly determining distances between neighbor nodes. In [8], locations of wireless sensor nodes which observe by their sensor devices according to their application programs and communicate by their wireless communication devices to forward sensor data messages are determined based on tradeoff between observation QoS which is quality of sensor data and communication QoS which is wireless transmission quality. In [17], in order to connect a sub sensor network consisting of wireless sensor nodes randomly distributed around the observed object to a sink node, surplus mobile sensor nodes moves to make a multihop transmission route between them. Due to the random distribution of wireless sensor nodes, some of them do not contribute to observe the object since their observable range do not contain it. Hence, the surplus sensor nodes move to connect the sensor nodes around the observed object to the sink node by configuratio of wireless multihop transmission route. Further more, DTN (Delay-Tolerant Networks) routing methods [6] are also reasonable for transmission of data messages by combination of forwarding and mobility.

## III. Proposal

### A. Highly Connected Sensor Networks

As discussed in the previous section, there are some proposals for achieving high connectivity and high communication quality by using a few numbers of intermediate mobile wireless nodes in sparsely distributed wireless sensor networks. These proposed methods are classifie into the following three categories:

(1) Densely distributed intermediate wireless nodes.
(2) Connectivity maintenance with mobility of intermediate wireless nodes.
(3) Introduction of DTN transmissions.

This paper discusses about (2) and proposes a novel method. Here, the applied systems are considered to be composed of autonomously mobile wireless nodes executing application programs such as mobile robots with sensors, actuators and processers. Communication among these mobile wireless nodes is supported by dedicated intermediate wireless nodes with mobility and wireless communication devices whose objective is provision of higher connectivity and required communication quality (Figure 1).

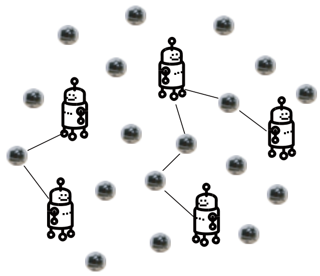

Figure 1: Highly Connected Network with Dedicated Intermediate Nodes.

The following two problems should be solved:

(1) Configuratio of wireless multihop transmission routes.
(2) Maintenance of wireless multihop transmission routes.

For configuratio of a wireless multihop transmission route between mobile wireless nodes executing application programs, there are an on-demand and a preliminary routing methods. In the former, no route maintenance overhead is required while no communication requests; however, in cases of occurrence of transmission requests, (1) acquisition of the location of the destination mobile wireless node, (2) determination of dedicated intermediate wireless nodes to configur a transmission route and (3) route configuratio are required to be realized. For (1) and (2), locations of all the possible destination mobile wireless nodes are managed continuously in a dedicated server node or advertised each time the locations are updated. However, communication overhead is high and higher connectivity among all the mobile wireless nodes is mandatory.

In usual management of mobile wireless networks, there are some synchronization time when all the mobile nodes return to the initial locations, e.g. for battery power charge. Thus, at this synchronization time, all the dedicated intermediate mobile wireless nodes also move to their initial location where all the mobile nodes and the dedicated intermediate nodes are connected in a wireless multihop communication manner. Then, even with autonomous mobility of the mobile wireless nodes according to application programs, the connectivity of the network is maintained by mobility of the dedicated intermediate mobile wireless nodes which also provide required communication quality.

### B. Dedicated Intermediate Mobile Nodes

In order to assure connectivity of a mobile wireless multihop network even with autonomous mobility of wireless

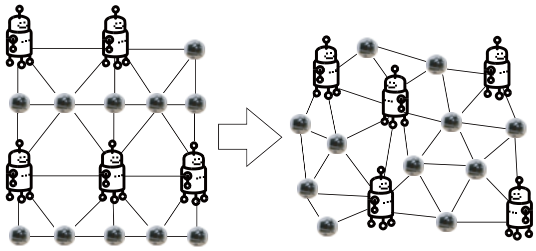

Figure 2: Connection in Initial Locations and Maintaining Connectivity.

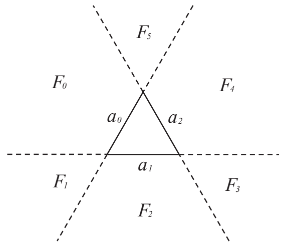


Figure 3: Location of Neighbor Nodes and Receipt Directional Antennas.

node executing application programs, the proposed dedicated intermediate mobile wireless nodes are required to devise the following functions:

- Detection of mobility direction and distance of neighbor nodes.
- Determination of their mobility direction and distance to maintenance of connectivity.
- Movement according to the determined mobility.
- Receipt and forwarding of data messages as intermediate nodes.

One of the well-known methods to achieve location information of neighbor nodes is combination of periodical acquisition of its most up-to-date location information by using GPS devices and its broadcast advertisement by piggybacking it to periodical 'hello' control messages as in GPSR [10] and FACE [2]. Here, by achieving relative locations of neighbor nodes, it is possible to calculate the proper location to maintain connectivity and communication quality. However, as mentioned in [12], location information achieved by using GPS devices contains certain errors and the induced direction and distance of mobility is not always correct. In addition, it is impossible to apply to indoor mobile wireless networks. Another well-known method is based on RSSI of periodically broadcasted beacon message whose receipt signal power suggests the change of distance to the source neighbor node. Various papers in which wireless nodes estimate distances to their neighbor nodes by using RSSI [16]. In real wireless networks, receipt signal power is not uniquely determined by distance, it is difficul for theoretical transmission models as a disk model [2]. However, within a short observation period, receipt signal power from the same direction almost monotonically decreases according to increase of distance. Hence, changes of distances are expected to be correctly estimated by measurement of the receipt power of periodically transmitted 'hello' control messages. In addition, in order to achieve the directions to the locations of neighbor nodes and their mobility, multiple directional antennas with different directional faces are devised to the dedicated intermediate mobile wireless nodes.

Figure 3 shows an example of three directional antennas $a_0$, $a_1$ and $a_2$ mounted on mobile wireless nodes. Though there may exist various reflecte waves according to the environmental effects, most powerful signal usually arrive directly. Thus, $a_0$, $a_1$ and $a_2$ receive wireless transmission signals from neighbor nodes in $\{F_0, F_1, F_5\}$, $\{F_1, F_2, F_3\}$ and $\{F_3, F_4, F_5\}$, respectively. On the other hand, a location of a sender neighbor wireless node in $F_i$ as shown in Figure 4 is estimated by using a combination of antennas receiving wireless transmission signals and comparison among receipt signal power. In addition, by continuous observation of sets of receipt antennas and receipt signal powers, changes of elements in the polar coordination system of mobility of neighbor nodes are estimated.

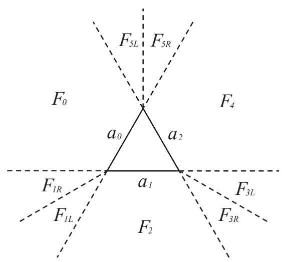


Figure 4: Estimated Location of Neighbor Nodes by Continuous Observation.

On detecting mobility of a neighbor node by change of receipt signal direction and power, a dedicated intermediate mobile wireless node should require to move to the location where network connectivity and communication quality are maintained. That is, it moves after the moving neighbor node under consideration of maintenance of connectivity and communication quality in wireless links to the other neighbor nodes. Here, a widely available 4-wheel mobile node as shown in Figure 5 moves along a detour route if its initial direction is different from the direction to the moving neighbor node as in Figure 6. Thus, the moving period may be longer. In the worst case, the moving neighbor node is out of its wireless transmission range and it loses sight of the moving neighbor node which makes impossible to move after it any more. As shown in Figure 7, this broken wireless link problem caused by detour mobility may be solved by changing direction of the node by differently directional rotation of right-hand and left-hand wheels without changing its location. However, this change of mobility direction also requires waiting time before mobility after the moving neighbor node, it may be out of its wireless transmission range.

Therefore, this paper proposes an introduction of sphere dedicated intermediate mobile wireless node for maintenance of connectivity and communication quality in Figure 8. In a sphere container, a driving module with three motors whose directions are 120 degree different each other is included. Each motor works with its proper rotation speed and its driving wheel contacting to the inside surface of the sphere container rotates. Then, the mobility created by the rotation of the three wheels are composed to realize the required mobility direction. The sphere surface contacts to the ground at a point and the node moves in any direction with zero turning radius (Figure 9). Thus, the broken wireless communication links caused by mobility of neighbor nodes are never caused by the restriction of the mobility performance of the nodes.

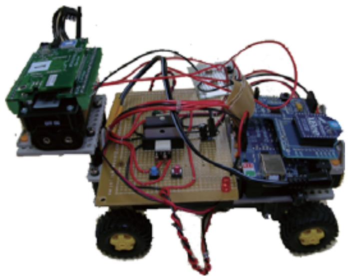

Figure 5: 4-Wheel Mobile Node.

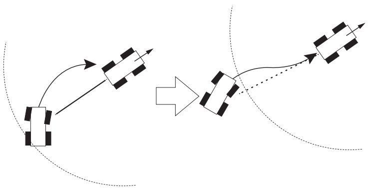

Figure 6: Detour Mobility of 4-Wheel Mobile Node.

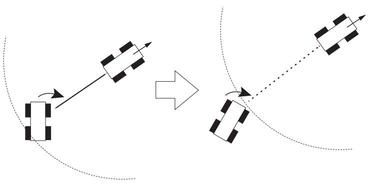

Figure 7: Circular Mobility of 4-Wheel Mobile Node.

## IV. Implementation

This section explains an implementation of the sphere dedicated intermediate mobile wireless nodes proposed in the previous section. A driving module and a communication

Figure 8: Sphere Mobile Wireless Node.

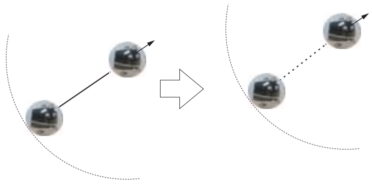

Figure 9: Zero Turning Radius Mobility of Sphere Mobile Wireless Node.

module are contained in a sphere container (Figure 10). The driving module consists of a microprocessor board for control, motor drivers, motors and driving wheels. The wireless communication module consists of a wireless network interface and directional antennas. These modules are mounted on a circular board. The directions of the motors are 120 degree different as in Figure 10. The directional antennas are also mounted with 120 degree difference, i.e., they are on the edges of a regular triangle as shown in Figure 11.

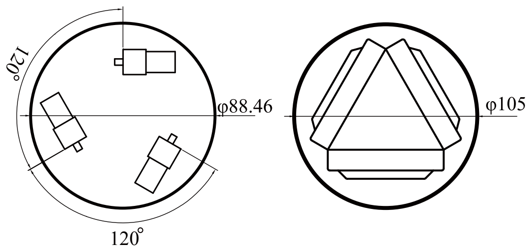


Figure 10: Arrangement of Motors and Antennas.

Figure 12 shows a system architecture. Mobility and communication control is implemented by a custom software for Arduino [1] microprocessor board which realizes processing of control messages exchanged among neighbor nodes, estimation of mobility of neighbor nodes based on power and direction of receipt signals, selection of working directional antennas (i.e., scheduling of the antennas), determination of its mobility and indication to the motor drivers. The wireless communication module and the directional antenna are FDE-

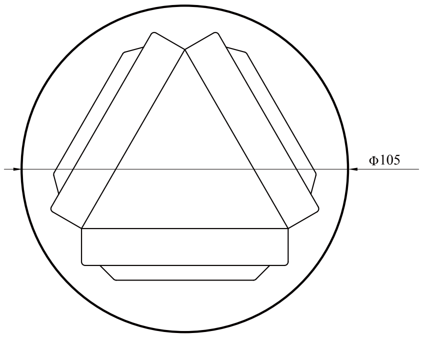


Figure 11: Arrangement of Directional Antennas.

02 and FAA-01 produced by Futaba corporation. The wireless communication module and the Arduino microprocessor board are connected through a serial communication line for exchange of control messages and the receipt signal power information. On receipt of messages from the communication module, the Arduino microprocessor request the receipt signal power to evaluate the direction and the distance to the sender neighbor node. Then, by comparison of the stored direction and distance information, it estimates the relative mobility of the neighbor node and determines its mobility. Hence, the indication to the motor driver is calculated. The rotation speed of the DC motors produced by S.T.L.JAPAN is controlled by the motor driver TA7291 produced by Toshiba Corporation and the mobility of the node is created by vector addition of the mobilities caused by the DC motors.

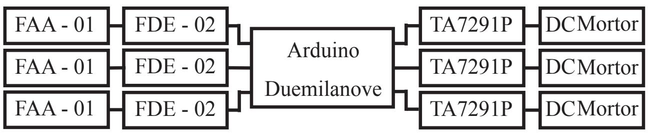


Figure 12: System Architecture.

## V. Evaluation

In order to apply the proposed dedicated intermediate mobile wireless node to dynamically configurabl mobile wireless sensor networks, it is required to estimate the mobility of its neighbor nodes and to move properly to keep connectivity and communication quality. This section evaluates the performance of a prototype mobile node.

For evaluate the performance of the wireless communication module, receipt signal power is measured by using two prototype nodes 10–90m away. PER (packet error rate) and BER (bit error rate) are measured by using transmission test FDE02TJ developed by Futaba Corporation. Here, 50 packets with 200 bit per packet PN9 data are transmitted. Figure 13 shows the results. In a wide range 30–50m distance between the prototype nodes, receipt signal power is about -80dBm and the error rate is acceptable. However, if the distance is over this range, the communication quality is drastically reduced. Thus, for maintenance of connectivity, the mobile nodes should move to keep the receipt signal power higher than this threshold -80dBm.

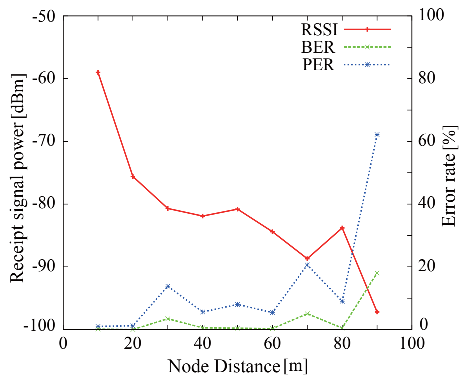


Figure 13: Communication Quality.

As discussed in the previous section, the prototype node has three directional antennas and the location of its neighbor nodes is achieved as one of the nine areas in Figure4. Within an area, it is impossible to achieve more precise location. Thud, the prototype node moves back and forth along a line to the median point of the area as in Figure 14. By using this mobility strategy, mobility performance to follow a neighbor node is evaluated in simulation. In a 600m テ 00m square area, initially two nodes are randomly located whose distance is less than 30m. One node moves according to the random direction mobility model [3] with 1m/s speed and the other follows it to keep the distance less than 30m. The simulation results of 10,000 trials are shown in Figure 15. Here, the connection is kept for longer than 4,500 second in more than 46.9% trials. An average following duration is 3,700 second and the proposed strategy is acceptable to keep the connectivity and communication quality.

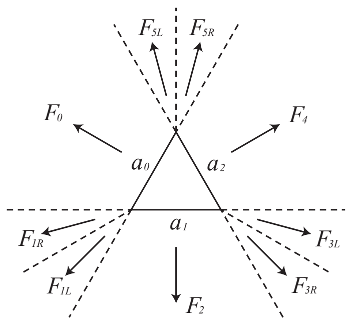


Figure 14: Mobility Directions.

## VI. Conclusion

This paper proposes a dedicated intermediate mobile wireless node to maintain connectivity and communication

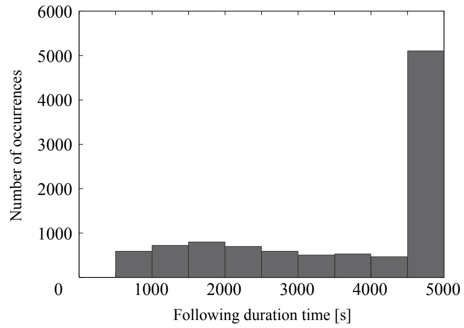


Figure 15: Following Duration.

quality for QoS based mobile wireless sensor networks. In order for better tradeoffs between observation quality and communication quality, the intermediate nodes are required to achieve their desired locations and to move rapidly. The proposed prototype determines its mobility direction by multiple directional antennas and a simple algorithm and moves with zero turning radius with sphere shaped node. In future work, performance of cooperation of multiple prototype nodes is evaluated.

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