Decentralized Cooperative Communication Framework for Heterogeneous Multi Agent System

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***Abstract*—**This paper examines the cooperative communication of multiple agents with no parent-child relation or hierarchy. In this communication framework, the multi agent communication must not be affected by the communication network failure between robots. Under this condition, a new communication framework was proposed which has allowed each agent to share the local information with reliable data delivery using peer to peer networking schemes. In this work, the whale communication call and echolocation concept were applied. The experimental results validated the communication reliability and performance.

***Index Terms*—**cooperative, multi agent, decentralized, communication framework.

I. Introduction

Generally multi agent system group architecture is categorized into centralized model and decentralized model. For centralized model, one agent will act as central control unit thus manages and controls the group; decides all the decision and communicates to all agents. Although this model able to manage the global communication, the main agent requires a powerful processing unit to achieve the mission. Otherwise, bottle-neck in terms of communication and processing time will occur and eventually causing mission delay and failure. While for decentralized model, each agent will uses individual local information and decision. The model can recover from vehicles faults and permit different actuators and sensor to be equipped to the agent. However, the global localization and mapping limit this system [1]. In order to introduce global information, each vehicle must be able to communicate with each other and share information.

A. Motivation

Oceanography issues especially the global climate changes, global warming and biosphere have motivated the interest of many researchers. Several works such as [2]-[4] have revealed the solution for marine exploration and monitoring. The systems are capable to measure temperature, depth-averaged current, salinity, dissolved oxygen, acoustic backscatter and thus ease the surveillances activities. The challenge of deriving the true variability of ecosystems is the essential long-term and high-frequency monitoring and observations activities[3].

A number of researchers have investigated the oceanography issue with platform such as the ship, Human Occupied Vehicle (HOV), Autonomous Underwater Vehicle (AUV), Remote Operated Vehicle (ROV), sea-glider, boats and buoy[5]-[8]. However, for real-time monitoring activities, the vehicles will require several communication hub for data collection due to poor signal propagation for ocean water.

In order to compensate with the long term capability for wide-scale environmental monitoring, the cooperative surveillance system is the best solution. The cooperative systems will enable data fusion from several of platform thus gathered by station keeping platform.

B. Related Work

The potential of multi agent system is by expanding and increasing single agent ability in terms of efficiency and scalability of data [9]-[11]. However, communication and mutual exchange of information are crucial in a cooperative multi robot system [12]. The communication framework contributes to all critical factors determining the stability of a group of agent [13].

However, wireless communication stability is not consistent due to environmental noise which will contribute to signal failure. Thus, it will affect the whole cooperative agent when the central unit breakdown [14]. Therefore, by implementing the decentralized cooperative architecture, the issue of dependencies between agents can be overcome. Several works have used the decentralized and mesh networking in their design [15]-[16].

In mesh networking, the topology allowing data to hop from node to node. However, if the nodes are dependent of each other it will also affect the network failure; hierarchy nodes dependencies such as coordinator, router and end device. In the approach proposed in this decentralized cooperative communication (DCC)

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framework, all nodes which representing the agents were independent in the communication system thus they will not affect the cooperative team mission with any changes of group members with simple network setup and self healing.

C. Contribution

In contrast to the previous framework, a decentralized cooperative system without dependencies of parent-child relation which combines multiple heterogeneous agents and offers longer range communication framework was proposed. Moreover, this framework consists of two types of agents, where beacon or buoy representing the static agent and blimp representing the mobile agent. The communication exchange between these two types of agents has introduced an environmental friendly monitoring system that preserves natural value of the selected area. The novelty of the approach is the communication framework of these two types of agents. Each agent shares the same role in the communication system thus; any changes on cooperative team will not affect the system and stop the mission. The computation of task for the agent was done by individual agents and used the relative measurement between agents as the range measurement.

The paper is organized as follows: Section II introduces communication framework for the proposed decentralized cooperative multi agent system. Section III deals with the new communication framework. The communication data reliability and performance are presented in section V. Finally, Section VI concludes the paper.

II. COMMUNICATION FRAMEWORK

In this communication framework, the mesh routing protocols were used to incorporate the egocentric data and estimated the distances between agent. In this communication framework, whenever the communication fails due to weak signal or system breakdown, it has the capability to self healing by generating alternate path. In addition, all agent can route data and interchangeable. In multi agent system, this feature is important to accomplish the desired mission.

A. Design Objectives

The new communication framework is used to support the multitude of ocean-based measurement and monitoring requirements suited to the Malaysian maritime ecosystems. Thus, it has facilitated the decision making, and served as an early warning system to allow remedial measures and subsequent action to be taken.

In order to preserve and protect the unique marine and natural value, buoy which acts as beacons is used as an information transmitter for the selected monitoring area. By integrating the blimp as a mobile agent has allowed to derive the true variability of ecosystems is the essential long-term and high-frequency monitoring and observation.

B. Decentralized Cooperative Multi Agent System Description

The heterogeneous multi agent system consists of three blimps as mobile agent and six buoys as static beacon. In this evaluation, each agent is equipped with IMU and compass for odometry data, GPS for localization purposes, camera for bearing measurement and wireless module. The beacon consists of oceanographic, meteorological and water quality sensors with GPS and wireless module. The hardware design for agent and beacon are shown in Fig. 1.

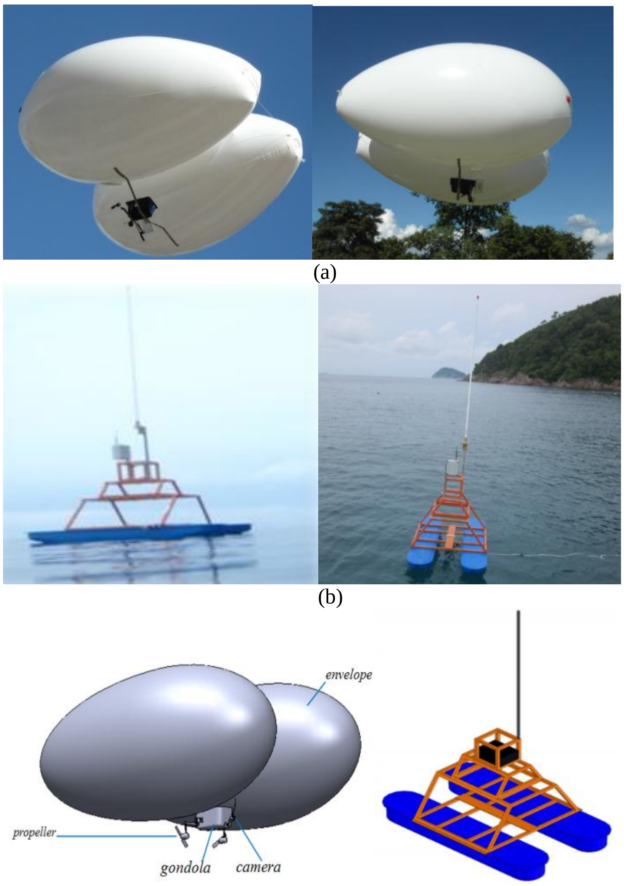


Fig. 1. Hardware design (a) mobile agent-blimp (b) static -Buoy (c) Solid work drawing : Blimp (d) Buoy

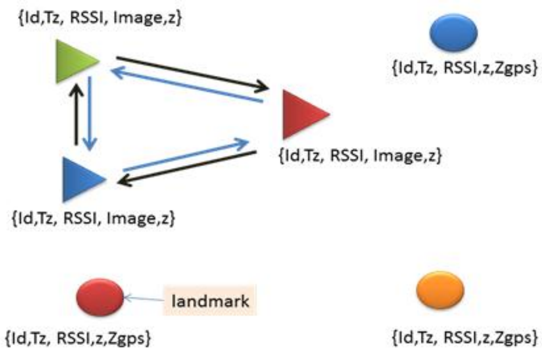


Fig. 2. The mobile agent makes inter-agent measurement

Fig. 2 illustrates the networking concept in this design where {Id,Tz, RSSI, Image,z} are the data shared between agent, Id represents the agent unique identification, Tz is the time stamp, RSSI is the received signal strength indicator represents the range value, Image is a one frame static image, z is the measurement data and Zgps is the latitude and longitude for location.

The DigiMesh network topology used in this design was the peer to pear topology where nodes is one type and homogenous. This network is more flexibility to expand the network and offers higher interference tolerance using the frequency-hopping spread spectrum (FHSS).

C. Communication Overlapping

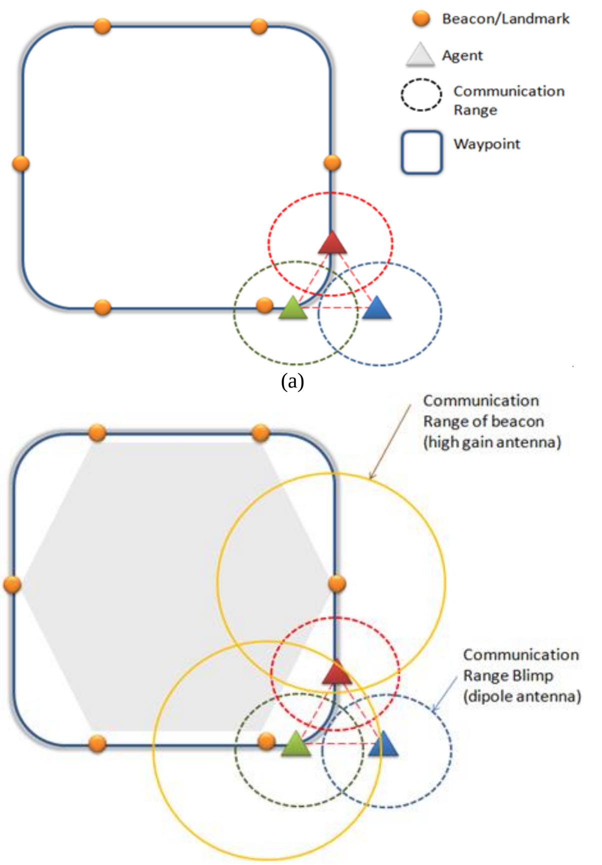


Fig. 3. Cooperative communication framework concept (a) Navigation setup (b) Antenna setup (c) Signal coverage as the mobile platform move contributes to signal overlapping.

By introducing the loop closure to the navigation path, the uncertainty to mobile agent pose will be reduced. While the hexagon beacon formation produces good communication signal overlapping. Fig. 3 shows the navigation scheme and agent allocation. This idea has a great impact on the localization and mapping of the mobile agent. However, the beacon will be in sleep mode until the RF data from the agent lies within the communication range.

The key characteristic of this design is that all the communications between agents are asynchronous. In this implementation, the beacon was equipped with high gain antenna with characteristic of 8 dBi, vertical polarized and omnidirectional base station. While, the moving agent used dipole antenna with 2.1 dBi gain value. In this way, the beacon will cover longer communication range and offer better outdoor RF line-of-sight (LOS).

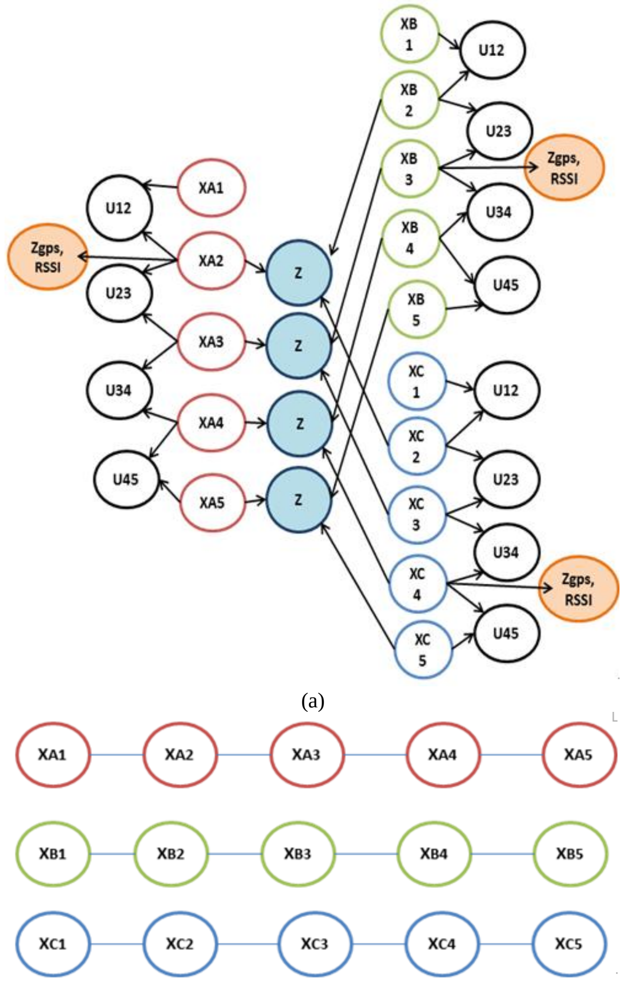


Fig. 4. (a) Directed graphical model of all states and data (b) Local Markov chain for blimp A,B and C.

System model: The decentralized cooperative communication and information exchange was presented in Fig. 4. The graphical model consists of pose state *(X_k)*, measurement data *($U_{k-1,k}$)*, location *(Z_{gps})* and distance *(RSSI)* and inter agent measurement *(Z)*. In multi agent system, generally the system model is given by

States pose of agent *i*

$$x_{i,k} = g(x_{i,k-1}, u_{i,k}, E_k), \forall_i \in N \quad (1)$$

let N represents the unique identification of all agent. Measurement data of robot *j* with respect to robot *i* reference frame is given by

$$y_{i,k}^{j,i} = h(x_{i,k}, x_{j,k}, \delta_k), \forall_i \in N, \forall_j \in N, i \neq j, d_k^{j,i} \leq r_v \quad (2)$$

If the agent is within the communication range, r_v then the data exchange is performed. During the off range, agent is unable to send data packet and should wait for valid communication data. The TX mode performs the acknowledgement (ACK) of each transmit packet for reliable delivery. If the TX module has yet to receive the ACK in allotted period, a new RF initialize will be transmitted. After receiving and acknowledging the data packet, RX mode proceeds to next frequency and listen to new data or re-transmit and check the pending data until the transmission is completed.

$$U_k = \{U_{i,k} | i \epsilon N\} \quad (3)$$

Equation (3) represents the set of odometry information from all agents at time step k,

$$Y_k = \{y_{i,k}^{j,i} | i \in N, j \in N, d_k^{j,i} \leq r_v\} \quad (4)$$

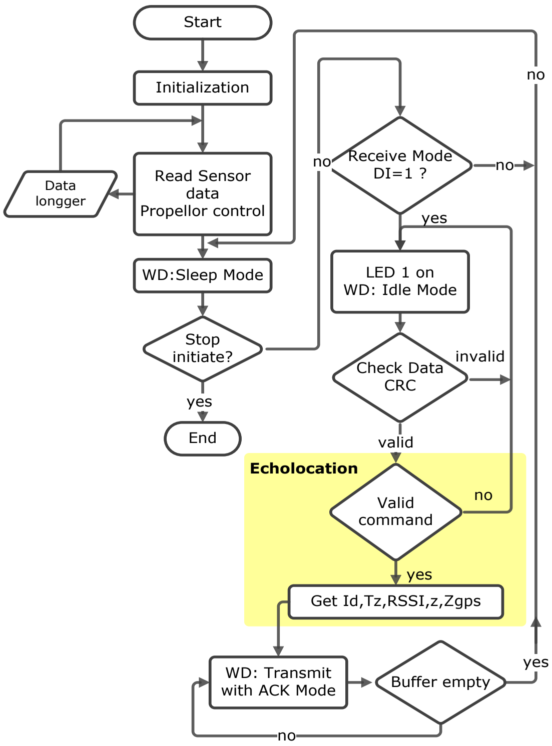
Equation (4) represents the set of all relative measurements from all agents at time step k, within the communication range,

$$Y_{i,k} = \{y_{i,k}^{j,i} | j \in N, d_k^{j,i} \leq r_v\} \quad (5)$$

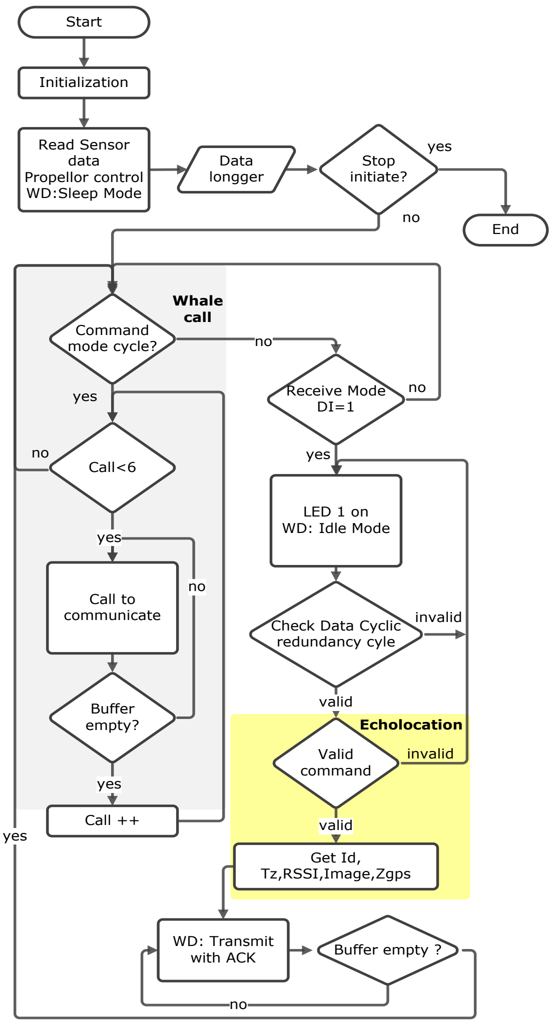
where k represents the time step, $x_{i,k}$ represents the state (pose) of robot i, U_k represents the odometry information of robot i, g is the state transition function, $E_k$represents the environment noise, $y_{i,k}^{j,i}$ represents the measurement, h is the measurement function, $\delta_k$is the measurement noise, $d_k^{j,i}$ is the distance between robot i and j and r_v is the measurement range limit.

Equation (5) represents the set of all relative measurement made by agent i at time step k and represents single agent relative measurement. In this communication framework, the peer to peer topology implemented the coordinator, router and end devices. All nodes were equal in which they shared the roles of master and slave. The RF modules remained synchronized with no master/slave dependencies.

III. Communication Model



(a)



(b)

Fig. 5. Flow chart of the novel communication framework using the whale call and echolocation concept (a) Buoy (b) Blimp

In this novel communication model, each agent was spaced far apart as the communication was done in long range. Motivated by the whale communication concept, the call and echolocation were applied in this work [17]. Fig. 5 illustrates the flowchart of the communication framework.

The whale call and echolocation concept were based on a study conducted by biologist Hal Whitehead. The variations in vocalizations between clans are defined in group; Group A: "Click-Click-Click-Click-Click," Group G "Click-Click-Click-Click-pause-Click," Group T "Click-Click-pause-Click-Click.". In this work, we have selected a clan song variation of Group A:"Click-Click-Click-Click-Click" codas which represents the call for beacon and blimp within the range and echolocation for the response of the agents.

IV. Results and Discussion

A. *Communication Reliability*

The communication reliability tests were performed to validate the reliability of distances measurements using the Signal Strength Indicator (RSSI) value. An experimental evaluation was done using two types of mesh networking protocol (1) Zigbee and (2) DigiMesh. In this setup, the wireless module used dipole antenna with 9,600 bps throughput data rate.

Zigbee: The modules operated within ISM 2.4 GHz frequency band. In mesh networking, ZigBee topology defines the nodes as the coordinators, routers and end device which play different roles. Fig. 6 illustrates the network framework for Zigbee.

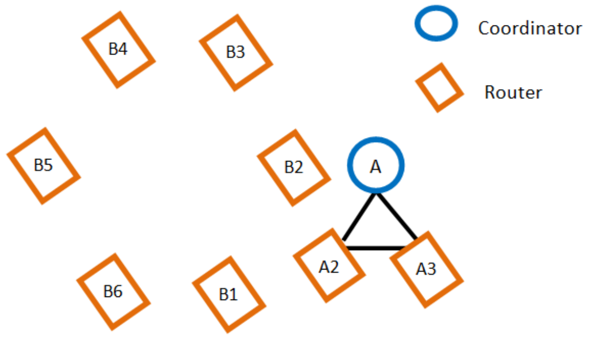


Fig. 6. Network framework using Zigbee

An experiment using the Zigbee RF module by Digi international was performed using Xbee2 2mW Chip antenna. In this experiment, the wireless devices were tested in free space (outdoor with LOS) environment; 16 distances points were considered. Each distances measurement was reported 5 times. The performance of the device was plotted in Fig. 7.

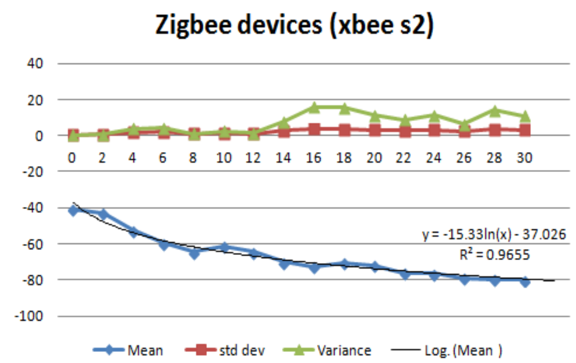


Fig. 7. Outdoor (LOS): Distance, m vs RSSI dBm.

The deviations of collected samples were small approximately less than 5 % from the average values. The R^2 value of 0.9655 indicated that the output fitted the real data well. However, this topology required minimum of one coordinator in a network. If the coordinator nodes breakdown, the whole operation in the network will fail.

Digimesh: The modules operated within ISM 900 MHz frequency band. This homogenous network protocol only has one node defined as DigiMesh nodes without needing to define the coordinator, router and end nodes. The peer-to-peer networking topology was chosen which offered no parent-child relation and all nodes were interchangeable. Fig. 8 illustrates the network framework for DigiMesh.

In this framework, all nodes were allowed to sleep hence, increased the battery life. When the mobile agent is moving, the beacons will be in sleep mode until the serial byte is received on the DI pin from the agent. Repeater mode was not allowed for the mobile agent in this framework design in order to avoid wrong distance measurement.

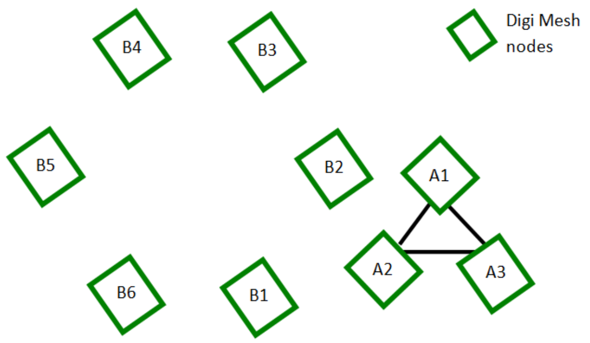


Fig. 8. Network framework using Digi Mesh

In this experiment setup, two types of power levels were tested on the wireless devices which were 1m Watt and 1 Watt; 14 distances point were considered. Each distance measurement was reported five times. The performances of the device were illustrated in Fig. 9 and Fig. 10.

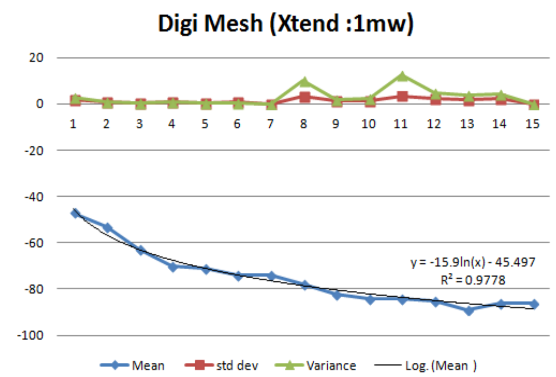


Fig. 9. Outdoor (LOS): Distance, m vs RSSI dBm

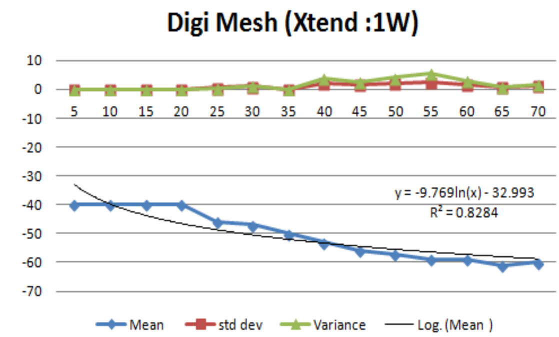


Fig. 10. Outdoor (LOS): Distance, m vs RSSI dBm.

As it can be seen in Fig. 9, the RSSI value deviated approximately 1.4 from the average value with R^2 value of 0.9778. This result indicated the highest R^2 value compared to the Xbee module. In Fig. 10, the RSSI value deviated approximately 0.9 from the average value with R^2 value of 0.828. As can be observed, the RSSI value for the ranges between 5~20 m have reported the same dBm values. In fact, a fine log trend was reported at 30~70m with R^2 value of 0.9775. This revealed that the transmitted signals were affected by power level.

Therefore, in the communication framework the beacon used 1 Watt power level to provide longer range to the RF signal to cover the selected monitoring area. Due to constant value of RSSI for shorter distance on the 1Watt module, it was not suitable to be used for mobile agent. Therefore, the mobile agent was set with 1mw power level to give more precise RSSI values for better inter measurement data.

B. Range Test

In this experiment, 100 packets of data were sent for each distinct distance. The good/bad received packets were recorded. Fig. 11 shows the range test percentages for 70 m range.

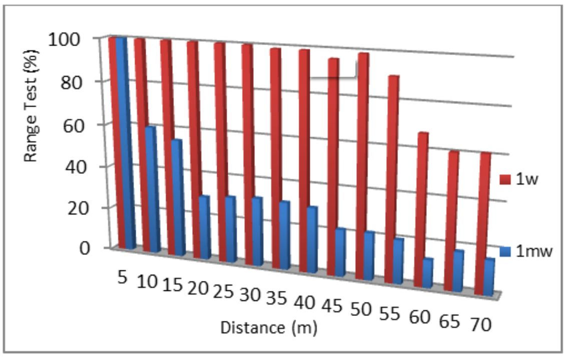


Fig. 11. Successful packet received via distance

The 1W module gave excellent results compared to 1mW power level. However, the 1mw module was capable to produce reliable data transmitted between 0~15 m.

C. Transmission Delay

TABLE I. PACKET TRANSMIT

Transmit length(bytes)	Received packets/s
32	4
64	3
128	2
256	1
512	1
1024	1

In this experiment, a number of good received packets per seconds were tested between beacon and mobile agent. In this setup, the beacon was attached with marine antenna and mobile agent with dipole antenna. The transmitted ranges were tested within 6~50 m and height difference of 7 meter. Table I shows the length of transmitted data and received packet.

Table I summarizes the communication latency of the Xtend module. The data transmission was affected by the size of the packet. As we can see, an acceptable latency was shown in the results for 1024 bytes of data. However, the delay was also affected by the distances and environmental noises. By choosing proper environment setup, it contributed to better transmission time and number of good received packet.

D. Centralized vs. Decentralized Approach

Here, we compared the number of messages transmitted based on centralized and decentralized approach. In centralized approach, every agent needs to transmit the information to the central unit before decisions are made. In the centralized approach, the total number of messages transmitted over the network is given by

$$n_c = b \times a \times \frac{t}{f}$$

For decentralized approach, decision can be made by individual agent without the need of central unit. The total number of messages transmitted over the network can be written as

$$n_d = a \times \frac{t}{f}$$

where b is the number of beacon/landmark nodes, a is the number of mobile agent in one transmission range, t is the total time and f is the transmission frequency rate [18]. Fig. 12 and Table II show comparisons of these two approaches with total experiment time of 60 seconds with number of landmark of three and number of mobile agent of also three in one transmission range.

TABLE II. COMPARISON OF CENTRALIZED AND DECENTRALIZED MESSAGE TRANSMISSION

a	b	Centralized	Decentralized	ndc(%)
1	2	120	60	50.0
1	3	180	60	66.7
1	4	240	60	75.0
2	2	240	120	50.0
2	3	360	120	66.7
2	4	480	120	75.0
3	2	360	180	50.0
3	3	540	180	66.7
3	4	720	180	75.0

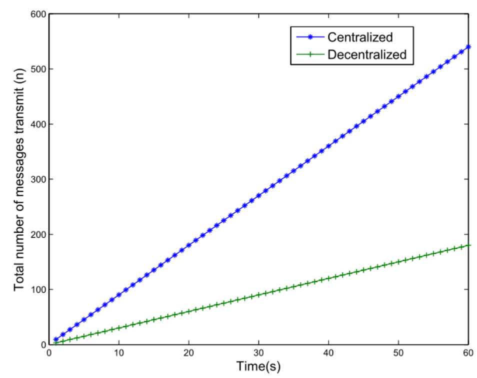


Fig. 12. Comparison of centralized and decentralized approach

The comparison showed that decentralized approach exhibited excellent reduction of number of message transmission between nodes with more than 50% reduction. Moreover, it will not affected the whole cooperative agent when the central unit breakdown

V. Conclusion

This paper has demonstrated that the new communication framework can perform reliable cooperative decentralized communication. In this communication framework, the mesh routing protocol was used to incorporate the egocentric data and estimate the distances between agents. It showed that the model was free from parent-child relation which provided more robust mesh networks for the heterogeneous multi agent system. Any agent may enter or leave the network without causing system breakdown. In addition, with the benefits of not relying on coordinator/gateway to maintain time synchronization. A novel communication model was presented for the multitude of ocean-based measurement and monitoring system. The whale call and echolocation codas represented the call for beacon and blimp within the range and echolocation for the response of the agents. The experimental results showed that the communication reliability during the operation and data exchange. This validated the ability of the DCC framework to maintain the networking relationship.

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