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Development of Communication Link Perception for Decision Making in Mobile Agents

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Development of Communication Link Perception for Decision Making in Mobile Agents

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AUTHOR`S DELCARATION OF ORIGINIALITY

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ABSTRACT

Examination and comparison of Packet Error Rate (PER), Error Burstiness (EB), and Receive Signal Strength Indicator (RSSI) as communication connectivity management metrics for multi-agent mobile robot networks are explored in this thesis. Assessment Accuracy (AA) and Time To Process (TTP) are used as parameters for the comparison of metrics given that mobile robots are required to make critical decisions rapidly. The initial investigations are done with a mobile unit making PER, EB, and RSSI measurements at an increasing distance from a base station. A relatively linear relationship between PER and EB was discovered with a R^2 value of .967. Strong correlations between EB and PER were observed in areas between 0% and 50% PER. A communication aware algorithm was developed using both EB and PER to allow the mobile agent to assess the Link Quality (LQ) faster in scenarios of communication loss by scanning for error bursts.

DEDICATION

To my parents Ion and Camelia Pantelimon who have helped and supported me over the years. I am truly thankful for your dedication towards me.

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LIST OF ABBREVIATIONS/SYMBOLS

Abbreviation	Definition
AA	Assessment Accuracy
ACKS	Acknowledgements
AUV	Aquatic Unmanned Vehicles
BS	Base Station
CoCoRo	Collective Cognitive Robots
CPU	Central Processing Unit
EB	Error Burstiness
GPRS	General Packet Radio System
GPS	Global Positioning System
GSM	Global System for Mobile Communications
LQ	Link Quality
NMEA	National Marine Electronics Association
PER	Packet Error Rate
PWM	Pulse Width Modulation
RSSI	Received Signal Strength Indicator
SMS	Short message Service
SSDL	Scalable Data Delivery Layer
TTP	Time to Process
TCP/IP	Transmission Control Protocol/ Internet Protocol
UAV	Unmanned Aerial Vehicles
UGV	Unmanned Ground Vehicles
UV	Unmanned Vehicles
WiFi	Wireless Fidelity

Symbol	Definition
$T_{Decision\_PER}$	Decision making time for PER
$T_{Decision\_EB}$	Decision making time for EB
T_x	Transmission time of a packet
T_{ACK}	Time taken to receive an acknowledgement
$threshold_{EB}$	Maximum allowed EB
T_{Total_Avg}	Average transmission and acknowledgment receive time
$T_{Decision\,Making}$	Desired decision making time
W_{Size}	Window size

CHAPTER 1

INTRODUCTION

Expeditious improvements in UV (Unmanned Vehicle) technology have led to an increased popularity of their use for research purposes, particularly in the data acquisition sector. Multiple UVs can be networked to create UV swarms which are capable of working collectively to fulfill and accomplish mission requirements. UV agents working in unison are capable of collecting data more efficiently and can act as sensor networks As most current sensor networks are stationary the use of UVs improves research capabilities through more dynamic data collection.

Different communications and formation structures exist, however they all rely on a communication link. Competent information transfer between UVs as well as between UV and Base Station (BS) is a fundamental step to providing a robust and efficient communication link. Consequently, an unreliable communication link can fail to provide essential information such as navigational or sensor data, which can result in an unsuccessful mission. Therefore maintenance and understanding of this link is pivotal to advancements in information processing through a stable connection link for UVs.

The intention of UV swarms is full autonomy, therefore each UV should be perceptive of its link quality (LQ) and be able to make individual decisions. Understanding of its link quality allows a UV to make corrections if it senses a poor connection with the BS, and allow it to avoid losing connection and the loss of critical information. Requirements of LQ perception are speed to contend with agile moving UVs and accuracy in order to avoid over and under correction. In practice a tradeoff between these requirements is needed. Generally the examination of the ratio of successful packets to lost packets can give some insight of the quality of the communication link. Furthermore a large sample size of this ratio will lead to an increased accuracy of LQ, but since each additional transmitted packet requires a certain transmission and receive time, this will impact the decision making time.

1.1 Problem Statement

Communication LQ in small radios implemented on robotic systems are negatively affected by two major components: range and line-of-sight. To optimally acquire a good communication link a transmitter/receiver pair must be within a certain distance threshold which is based on the constraints of the hardware; this is defined as its range. As a radio moves further it is affected by a reduction in power density which is due to path-loss effects. Furthermore the transmitter/receiver pair must not be inhibited by any objects which do not allow the penetration of radio waves or do not allow a direct line-of-sight. The focus of this work is to combat the range limitations of hardware by examining LQ as it goes from good to poor.

Currently in multi-agent systems the primary focus is on control and navigation with limited work focused around communication management. Limitations in this field are due to the novelty of autonomous unmanned systems. Other issues include indentifying popular communication hardware used in current UV swarms which will help establish appropriate metrics for communication management. Accuracy and decision making time are the major criteria for these metrics in order to contend with the rapid movements of UVs. Finally for the development of autonomous multi-agent systems a classification of LQ should be developed.

1.2 Main Contribution

An assessment and classification is done for current multi-agent robotic communication systems used for sensor networking. Major communication structures are categorized as centralized and decentralized. Additionally two major formation control systems are identified as leader-follower and virtual structure. WiFi and XBee were found to be the most popular packet transmission communication used in current research. Through the analysis of previous literature communication was identified as an integral part of multi-agent robotic networks. An understanding of how to improve and maintain the communication link is imperative to multi-agent robotics systems. The development of a fully autonomous system requires each agent in its own capacity to be able to monitor its own connection. An increase in the separation distance between agents will increase the chance of communication deterioration because of path-loss effects. An agent equipped with a communication link perception algorithm can monitor its link and have the capability to correct this link in order to avoid losing connection.

Three potential metrics were identified: Packet Error Rate (PER), Received Signal Strength (RSSI), and Error Burstiness (EB). Each metric was individually tested on a moving mobile platform while recording packet transmission data. The mobile agent was programmed to transmit and to tabulate successful and failed transmission by keeping track of received acknowledgements (ACKS). This received data is referred to as the packet stream, where successful transmissions were given the value one and lost or unsuccessful transmitted packets were given the value zero. Analysis of this stream was done with PER and EB at increasing distances from the BS. EB was shown to have a linear relation to PER and was able to estimate the LQ faster.

Finally, the assessment of LQ was done through a combination of PER and EB values. PER in this work is the ratio of lost packets to the number of sent packets considered in a moving window. Window size optimization is also discussed in order to provide as close to real-time analysis of LQ as is practical. EB in this thesis is represented as consecutive lost/error packets. Larger consecutive errors are shown to yield a less reliable LQ. The combination of these two metrics allows for a communication aware system that can bridge the gap between accuracy and decision making time, which are trade-offs because accuracy increases with more data points at the cost of time. LQ is classified as one of three regions: good, tolerable, and unreliable. Good regions are ones which provide stable and constant LQ with zero PER, tolerable regions are susceptive to some loss but with .10 PER or less, and unreliable are regions with a volatile PER over .10 , they are also prone to EB of size two. Since multi-agent robotics are deployed with data collection as a primary focus, connectivity management is designed as a secondary process. The system developed is light-weight computationally and will not take away from mission objectives. Additionally the system is flexible to work on different robotic agents as ground and air units are known to work in conjunction.

1.3 Organization of the thesis

Chapter 2 reviews popular multi-agent systems used in applications and categorizes them based on communication structure and formational control. Advantages and disadvantages are listed for both centralized and decentralized communication structures. Additionally both leader-follower and virtual structure formation control systems are also compared. Different multi-agent systems with experimental results are summarized and their success and failures are highlighted. Finally the most used communication hardware systems are compared by five different parameters.

Comparison of PER, EB, and RSSI is done in Chapter 3 by examining the change of each in respect to distance moved away from the BS. Analysis is primarily focused around the examination of the change in LQ. A close relation between PER and EB is demonstrated. Experiments were conducted to test different values of EB stopping thresholds for the mobile agent. It is shown that each EB threshold corresponds with a different stopping distance and PER.

Chapter 4 details the perception algorithm developed from the hybrid of PER and EB. Window size optimization is discussed as different radios have different transmission speeds. A window size is chosen which was optimized for our hardware. A moving average PER was implemented through the use of this window and a maximum allowable EB threshold was chosen, which was determined through experimentation to improve LQ.

Future works and improvements are considered in Chapter 5 alongside the conclusion.

CHAPTER 2

SURVEY OF MULTI-AGENT COMMUNICATION STRATEGIES

Ground, sea, and airborne drones have become flexible tools for research and commercial applications in the military, agriculture, forest fires, chemical sensing, meteorological sensing and countless other rapidly evolving areas [1,2,3,4,5]. Their popularity has increased with the development of longer run times, higher payload capacities, improved stability, and increasingly accessible pricing [6]. Concurrently, the broad spectrum of communication and sensing technologies available for a wide variety of applications has been reduced in size and complexity to enable easier integration into robotic systems. Subsequently these advancements in individual drone performance have since better enabled the utilization of coordinated groups of drones or 'agents' [7]. Multi-agent deployments can increase both the diversity of sensory data possible and the spatial extent over which sensing can be deployed. Entire data fields can be harvested as opposed to single point sampling. Having multiple agents also promotes mission robustness through individual agent redundancy. While team deployments have many merits, some fundamental challenges remain that include determining the optimal control and/or coordination strategy [8]. Underpinning the success of the control philosophy and the coordination of the data collection is the requirement for a robust and efficient communication strategy [9]. In this paper our major focus is on the principal aspects of communications strategies critical to multi-agent drone formation architectures, mission planning, and communication hardware selection.

Multi-agent control and communication strategies often fall into one of two categories: centralized or decentralized architectures. The following sections will describe and compare these architectures and the sub-classes within them. Then, specific applications of these approaches will be discussed. Finally, we will offer commentary and recommendation for future research directions.

2.1 Communication Strategies for Mission Control

Presently there are two primary ways of routing information in a multi-agent system for mission planning, namely centralized and decentralized, where the following section will examine the strengths and weaknesses of each communication strategy. In the centralized approach a base station is utilized; the communication system can be described as point to multi-point as seen in Fig 2.1. In this configuration all computations and critical decisions are made at a central base, depending on the sensory data gathered [10,11]. The base station is able to communicate with each agent and exercise control over it. This affords a central location for human intervention in drone team operation should it be required. Further, having the central command centre bear the burden of control and communications tasks, the agents can have increased capacity for sensory infrastructure, payload, etc.. In this approach, each agent will communicate with the base station exclusively, not with other agents.

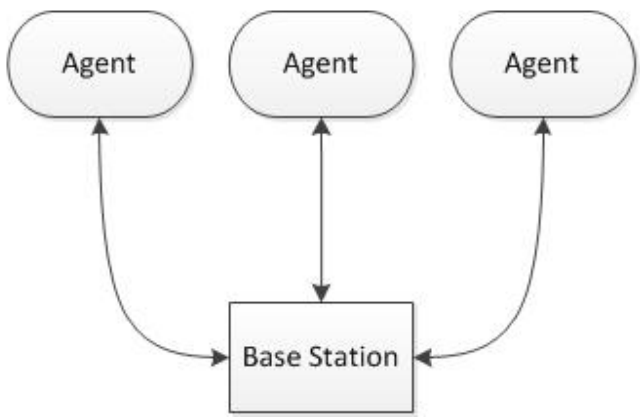

Fig. 2.1 Centralized Communication Strategy

In a decentralized approach as in Fig 2.2, communications are accomplished through direct agent-to-agent interaction, which can be described as a mesh communication strategy [12,13]. Each agent is capable of making decisions, which will ultimately be governed by a hierarchy or algorithm to ensure order. Decisions will be based on sensory data collected, and will vary based on the application. This approach eliminates the overhead of the communication through the base station and promotes more autonomous mission development. A key advantage to this architecture is that the multi-agent team is not limited by the communication range of the base station; further, each unit can work as an individual or in a team. Table 1 highlights the critical advantages and disadvantages of architectures.

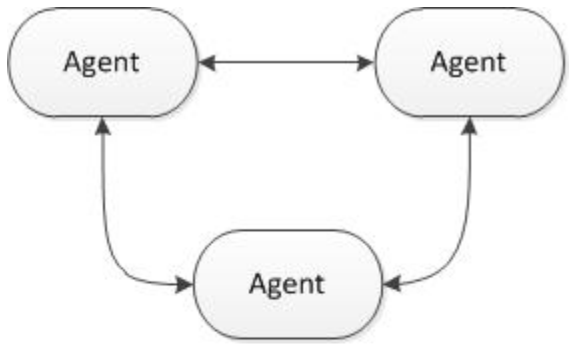

Fig. 2.2 Decentralized Communication Strategy

TABLE 2-1
Major advantages and disadvantages of centralized and decentralized control architectures

Centralized	Advantages	Disadvantages
	Central authority responsible for critical decisions	Communications limited to base station range
	No need for agent-to-agent communications	Complete reliance on base station availability
	Single agent loss has minimal impact on mission objectives	Computational requirements increase with addition of agents
Decentralized		
	Individual agent autonomy	Hierarchy or a coordination algorithm needs to be developed
	Not limited to central base station range	Strong inter-agent dependency will reduce mission robustness
	System scales well	

2.2 Communication Strategies for Formation Control

The two most common formation control strategies are leader-follower and virtual structure. In leader-follower, a leader is chosen and the rest of the agents are assigned as followers [14,15]. The group leader broadcasts its position information to the followers who then begin to follow the leader at an offset. Position information such as Global Positioning System (GPS) coordinates or National Marine Electronics Association (NMEA) strings can be broadcast through multiple mediums such as Wireless Fidelity (WiFi) also known as IEEE 802.11 [16] modules and/or Zigbee also known as IEEE 802.15.4 [17] radios. Each follower will have a predetermined offset that they follow depending on the shape of the formation required. Another option is to route the position information through a base station, which in turn would relay the appropriate information to the follower agents. Subsequently, distance and course offsets have to be chosen judiciously to avoid collisions. This system offers a simplified communications framework which is balanced by the risk associated with a single critical point of failure in the leader.

In virtual structure formations all the units are considered to be a rigid body and move as one whole group [18]. All agent positions are established relative to the centroid of a virtual body. To ensure proper orientation and collision avoidance, individual trajectories are constantly calculated. Each agent will be transmitting and receiving position information frequently, therefore a high speed and low latency system is critical. In addition to the previous requirements, a robust and capable controller is also required. It follows that controller complexity will scale with the addition of agents to the system. Further, it should be noted that constant feedback is required by the controller for each agent; thus increasing the overall communication requirement. This structure will provide a more robust result but it is reliant on the design of a suitably complex controller. Table 2-2 highlights the critical advantages and disadvantages for each approach.

TABLE 2-2
Communication implications for different formation architectures
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Leader-Follower	Advantages	Disadvantages
	Simple communications: One-Way Broadcast	
	Scalable to large group of followers	Single-Point of Failure (Leader)
	Simple to implement	
Virtual Structure		
	Each drone is given precise trajectories	Hierarchy or a coordination algorithm needs to be developed
	More robust	Strong inter-agent dependency will reduce mission robustness
		Dependent on controller

2.3 Multi-agent drone applications with communication strategies

Given the relative novelty of the drone sector, and the explosive growth in drone technology, few standards exist to serve as a basis of comparison among the great variety of research efforts. The authors have here endeavoured to broadly categorize a number of prominent multi-agent communication strategies from the literature in the context of their applications.

2.3.1 Centralized Base Stations

Bürkleetet al. [19] enhanced the ground station developed by Fraunhofer Institute of Optronics, System Technologies and Image Exploitation [20] and utilized it as the main control station to coordinate unmanned aerial vehicles (UAVs) and unmanned ground vehicles (UGVs). In this system, smart cameras were installed on the UAVs, which provided the operator with a real time view of agents, along with GPS coordinates and altitude. This information was transmitted to the ground station through a tiny WiFi module capable of network communication, which provided high data rates and long range. The ground station had four types of communication channels: broadcast, control, data, and co-op. The broadcast channel was used to reach all the UAVs at once with one message from the ground station. The control channel provided an individual link between a UAV and the base station; it was used to upload mission related information and tasks to the UAV over the air. Communications between two UAVs were opened through the co-op channel. Control among the multi-agents was hierarchical. Agents were assigned as team leaders, copter, or sensors. Team leaders controlled groups of sub agents and assigned tasks. Copter agents acted as data relays between groups of sensor agents and the team leader. In addition to the prototype, a simulation tool was used to assess different cooperation strategies and optimize different sensing techniques.

Another successful implementation of multiple UAVs through the use of a ground station was described by Alex Kushleyev et al. [21]. The ground system used was a Vicon motion capture system [22], which was capable of tracking each individual UAV. The control system was developed in MATLAB [23] and all the commands were sent via custom radio modules. Each UAV contained two independent Zigbee transceivers which operated at 2.4GHz and 900MHz. Inter process communication was used for non-time critical data sharing, as it was adjustable to different message passing and used Transmission Control Protocol/Internet Protocol (TCP/IP) sockets to send data between processes. The UAVs were split up in certain groups, and each group was controlled by the ground station, but there was no communication between groups. A novel idea used to further simply the complexity required each UAV in a group to follow the same trajectory but with a time shift. Multiple drones were capable of navigating in various formations while avoiding collisions. This effort was one of the most successful implementations of an indoor centralized approach; the only limitation of the project would be the challenges of applying the vision sensors in an outdoor environment. This is primarily because the cameras function best with a white background for contrast to easily identify the agents. The addition of environmental parameters such as wind could also drastically affect the stability.

A system to manage and program UAV swarms, called Karma, was developed in this research. Karma's goal was to create a hive-based system with a central controller and avoid agent to agent communication [24]. By eliminating the infield communication, the complexity of both hardware and software of each individual drone was reduced. All the computations were done at the central computer, called the "hive." This centralized version has the advantage of collective intelligence and was be able to better allocate resources. The hive determined how and where to send the UAVs, based on the mission objectives. Then, it provided the drones with a specific task, after the drone completed their objectives it returned to the base to recharge and drop off its data. A major assumption in this work was that it was always possible to locate the UAVs in a region. The hive itself had a central storage, called *Datastore*, which was updated as soon as the drones returned from a mission. This information allowed the hive to see its progress and if it could make different decisions to improve. A considerable advantage to the hive model was its adaptability, especially to loss of a drone. The hive was capable of understanding the loss of a drone and was able to reprogram and send other drones to that area. It was able to notice if an area was gathering information at a slower rate and to send more drones to increase the pace. In order to test the theory, a simulation environment was created based on *Jbullet* [25] called *Simbeeotic* [26] where a *mCX2* [27] radio transmitter was modified to accept radio controller (RC) commands through a universal serial bus (USB) port. The system was still in the early stages and undergoing additional testing.

An agricultural irrigation application underpinned by aerial photos and ground data loggers utilized a 900MHz Maxstream [28] modem for communications [29]. In addition, a 20dB antenna was used to provide a range of 3 miles. Synchronization of the transmitted images versus images logged on the UAV were sometimes problematic. *CR 206* data loggers from *Campbell Scientific* [30] were used as ground communication modules, they transmitted using a 915 megahertz (MHz) spread spectrum radio modem. They were able to send information every 15 seconds if another module is detected. The UAV was able to take pictures and collect data by following the certain predetermined waypoints. The project's major limitations included synchronization and lack of a more robust flight control.

The Collective Cognitive Robots (CoCoRo) system is formed around a floating marine base station and a terrestrial ground swarming the interest of conducting coastal/marine monitoring and search [31]. The ground swarm was equipped with accelerometers, compass, pressure sensors and energy sensors. For local optical communication infrared data association quadrature amplitude modulation was examined as it provided a communication rate of 119 kilo bit per second (kbps). In addition acoustic communications were studied given that acoustic waves travel well under water [32]. Underwater distance measurements were done considering the absorption properties of water, which are the frequency/wave-length, salt concentration, pressure and other parameters. The documented work was in early stages and preparation of a small-scale experiment was planned.

2.3.2 Centralized Leader-Follower

A centralized leader-follower approach qualifies as a subcase of the centralized base station architecture. Yun et al. developed a simulation to assess this particular multi-agent control/communication technique [33]. The approach focused on maintaining a formation while navigating a pair of UAVs to follow specified trajectories. The leader would transfer velocity and position measurements to the base station through a *FreeWave* wireless modem [34] which had a transmission rate of 115.2 kbps and a 20 mile range. The transmission protocol used was under the *QNX Neutrino* real time operating system. An encroachment zone was designed for each UAV to ward off collisions. UAVS were re-routed outside of one other's protected zones. The lead UAV would send data such as position and velocity to the ground computer that would perform the calculations and send it to the follower UAV. The flight simulation proved to be successful and the tracking error was less than 4 meters.

2.3.3 Centralized Virtual Structure

Unlike leader follower, in a virtual structure, the entire system is considered as a rigid body. There is no hierarchy in between agents, thus making it more robust then a leader-follower method. However, this often comes with additional control complexity. Sadowska et al. developed a virtual structure controller which could designed to offer stability and formation control [35]. To simplify the complexity of the dynamics, unicycle mobile robots were used. The simulation was done using two E-puck robots [36] that were controlled through a wireless Bluetooth connection, which would send the velocity for each motor. Position measurements were done using a camera and vision software. The virtual centre moved in a circular motion; one robot was placed ahead and one behind. The robots were able to reach their desired formations within 15 seconds. Time to organize was dependent on the specific application.

2.3.4 Decentralized and Virtual Structure

Li and Liu [37] claim that a decentralized approach is more desirable than a ground station based approach since it eliminates the communication overhead with the ground station. In this paper the UAVs are considered individual access points and are part of a self-configuring network. A *GumStix* computer [38] was programmed and attached to the onboard auto-pilot to act as the controller. Communications were achieved through the wireless Ethernet capability of the *GumStix* computer. The TCP/IP protocol was used to enable agent to agent communications. Each UAV was equipped with an autopilot system that tracked velocity, altitude, and heading. Reference trajectory, actual, and desired positions of the vehicles were used as inputs in the controller; which gave the new trajectories for each UAV. Flight tests were carried out with two UAVs and formation control was achieved. GPS error and wind gusts were the largest challenges to mission accuracy. This system eliminated the requirement of a ground controller, however, it also created a need for each UAV to be equipped with its own onboard controller. Further research is needed to test the system for more than two agents, as communications will become more complex.

2.3.5 Decentralized Leader-Follower

The creation of a small and inexpensive Aquatic Unmanned Vehicles (AUVs) that can operate in a swarm are examined in this paper [39]. Each individual unit consisted of a *Beagle Bone* [40] central CPU, along with a camera, triple axis accelerometer, triple axis gyroscope, and pressure and temperature sensors, along with a motor controller. Process algorithms were divided into three levels: controlling and sensor level, behaviour level and task level. The first level requested data from the multiple sensors and adjusted the motor speed. For external communication with the camera a 256 kbps serial interface was used. The experimental setup engaged a leader-follower approach, with the follower scanning and looking for a lead orange marker by way of the camera. At a range around 3 meters it was able to see and follow the leader. Challenges arose with the follower's inability to distinguish the leader front and back, which increased collision risk.

In another application of decentralized leader-follower, Varela et al. documented their efforts to assess pollution emitting sources by using a team of autonomous UAVs [41]. It focused on fixed-wing UAVs attached with chemical sensors that worked individually at first then as a team to find the source. All the data was logged on each individual agent, and was then retrieved upon landing. The coordination approach was based on three phases of operation, after takeoff the planes began in a spread formation. This allowed them to separate and cover the largest possible area to facilitate initial pollutant detection. This was done by increasing the distance between agents while remaining within a limited fixed radius of take-off origin. After completion of the discovery phase, the planes moved into a monitoring phase. Once they obtained sufficient data, they began to share the information with the other planes in the air. When a plane sensed a pollution value above the established threshold, it would then enter the search stage; where planes would work together to find the source of the pollution. This was done by comparing the averaged pollution values on the current plane versus its nearest neighbours, and based on the values it could change its course to seek larger values. The efficacy of the system is challenged by the tight response times required to match a moving formation with a moving target. Further, with multiple agents collectively seeking new positions based on a dynamic field of pollutant concentrations, the risk for collision is significant. Effective communication and subsequent collision avoidance systems will be necessary.

Increasingly, UAVs are being deployed by government agencies and police organizations to monitor large events and gatherings [42]. A unique and pragmatic element to the work of Oliveri and Endler was the use of existing cellular infrastructure for agent to agent communication, which mitigated the need for the creation of an entirely new communication network for the UAVs. Provided the agents were within cell tower range, the network infrastructure was relatively robust given the well established nature of current cellular networks. Each agent was equipped with smart phone electronics in order to join the network. Having a smart phone could provide some issues with smaller agents sensitive to payload weight. Requirements of the phone hardware were GPS, compass, 2G/3G/4G internet connectivity and the ability to run Java. The flight information that went to the phone would then be translated into pulse width modulation(PWM)for the flight controller. The translation process was designed to be quick enough so as not to affect agent flight controls. A communication middleware that was created called *Scalable Data Delivery Layer* (SSDL) [43] was used to communicate from UAV to UAV. The protocol used relied on the SSDL; which acted like a group communication and management function. Each agent would be in either of two states: Patrol mode or Swarm mode. Initially they all start in patrol mode and travel around an area of interest with set parameters. Ground control was capable of choosing one to become a leader and a number of UAVs to become slaves to it. The slaves would then form in a circle of a specified radius around the leader. This afforded a wider view of the area below for the cameras. The current focus of the work is the implementation and testing of the coordination protocol to be executed on the smart phone.

The spraying of pesticides by UAVs in an agriculture setting was examined in a paper by Costa et al. [44]. Feedback was given to the UAVs from on the ground wireless sensors to determine the areas to be covered. Information such as position and amount of chemical detected were given. This ensured that the UAVs would only spray designated areas. The UAV would periodically send broadcast messages to sensors in the field requesting chemical sensor readings and positions. The route would change if the readings were not the recommended threshold for that specific chemical. Simulations were carried out to test the management algorithm. Results were favourable with no wind and offered still promising results with simulated wind. Tests were also conducted with hardware to measure the communication time between a UAV and ground sensor using the *Xbee-Pro Series* [45] as the communication module. Further work is needed to explore the hardware and communication implication of using many sensors and multiple UAVS.

2.4 Common Communication Hardware Used

The communications sector in the rapidly burgeoning field of multi-agent robotics can be a challenging place, as developers attempt to balance factors like range, bandwidth, speed, power requirements, payload weight, compatibility, and cost. The most popular communication hardware is Wi-Fi modules, as they are routinely used in many processes and can be easily implemented in most systems. Some drawbacks include the overall size of the system and the required programming of ports to connect to the system. Wi-Fi technology ranges can be on the order of 100 meters or greater depending on the antenna used. Weight and cost can vary with each modem type but on average they are slightly larger and more expensive than Bluetooth or XBEE [45] radios. Complexity tends to be higher as more programming is required, and power requirements are significant as there is no sleep cycle. Bluetooth devices are small and lightweight products that can add 10m-100m of range functionality to a project. They have low power requirements since they have a sleep cycle to conserve battery power. They can currently be purchased for under 50 USD dollars. Bluetooth is intended primarily for point to point systems with minimal configuration requirements. Small omni-directional XBEE radios have been also used in many projects as they come in many different configurations. XBEE radios use the Zigbee protocol a simple low overhead system that can be used in point to point, point to multi-point, and mesh systems. They can offer ranges from 90m to a few kilometres depending on the model. They are low-power systems that have a sleep mode for extended battery life. The modules currently range in cost from 25-100 dollars. A less popular idea, but which holds some potential is the use of existing cellular infrastructure. This approach would fare well in urban areas but lack success in rural settings. Cellular technology can be lightweight (10 grams) and can provide ranges of over 8km depending on location of towers. Current average module costs are near 100 USD dollars; and they require roughly 700mA to 1000mA to operate. The complexity varies depending on the protocol used, options include short message service (SMS), Global System for Mobile Communications (GSM), General packet radio system (GPRS), and TCP/IP. For underwater projects acoustic communications are the best choice as RF signals would be heavily attenuated. Acoustic ranges may vary from 10 m to 1000+ depending, depending on cost. Further, these systems require a special housing for at depths of 6000m that add to the weight of the system which can be over 1 kg. Power requirements increase with transmission distance and can range from 5.5W to 18W. Complexity varies from model to model, but popular models use wireless Ethernet and RS-232 [46] communication protocols. Table 3 organizes the above mentioned information in a table format

TABLE 2-3
Popular communication hardware used in drone communications

Technology	Range	Weight	Complexity	Cost	Power Requirements
WI-FI [19,33]	MED	MED	HIGH	MED	HIGH
ZIGBEE [21]	MED-LONG	LOW	LOW	LOW	LOW
BLUETOOTH[35]	SHORT-MED	LOW	MED	LOW	LOW
CELLULAR[42]	LONG	LOW	HIGH	MED	MED
ACOUSTIC[31]	SHORT-LONG	HIGH	HIGH	HIGH	HIGH

2.5 Conclusions

In this review paper the most common communication and mission control strategies for multi-agent drone deployments were examined. In addition, different agent systems such as air, ground, and water vehicles were described to provide perspective on the variety of applications currently being explored. A majority of the work in this field remains in the simulation stage; some are nearing the implementation stage, as the coordination of drones is a complex problem. Even those efforts that have demonstrated success with multiple drones, have typically done so in an idealized, controlled environment and would need significant adjustments for real-world deployment.

Each system was categorized under the two major headings of centralized or decentralized. When considering centralized versus decentralized in a multi agent system, the decision is largely based on application. One size does not fit all. An ideal solution would be a hybrid of both systems, where the agents can act autonomously, still learn from each other, and concurrently have a central operator for offloading complex computational tasks as well as monitoring mission critical items like safety. Currently, time sensitive missions where information needs near-real time monitoring will fare better in a centralized architecture. While those less time sensitive applications may be decentralized, with the information downloaded from individual agents and analyzed at a later time.

The potential applications for coordinated, multi-agent drone deployments appear nearly boundless. Fortunately, (or regrettably), the choices for communication and coordination strategies seem to be nearly as unconfined. Developers must make their choices based on a balance of variables like range, bandwidth, speed, power requirements, payload weight, compatibility, and cost. The best balance will likely be that struck in the context of robustness, scalability, adaptability, and cost.

CHAPTER 3

ANALYSIS OF PER, EB, AND RSSI AS LINK QUALITY METRICS FOR CONNECTIVITY MANAGMENT

The rapid evolution of Unmanned Vehicles (UVs) has created many new possibilities for multi-agent sensor networks [47,48,49]. This enablement is largely attributed to advancements in battery technology and payload capacity in UVs [50]. The integration of specialized sensors on UV agents increases sampling abilities in three dimensions [51], which is particularly advantageous in large missions. This becomes increasingly powerful when multiple agents are used to create sensor arrays that may be configured for simultaneous measurements of field quantities (temperature, pressure, wind speed, chemical concentrations, etc.) [52]. Similar arrays of agents can also be used to deploy signals or substances. Subsequently, segments like the military, agriculture, and civic security are significantly engaged in this emerging field [53]. Coordination of multiple unmanned robotic agent deployments is not a trivial pursuit. Many engineering challenges remain to improve critical facets of multi agent arrays, specifically, formation control, communication management, and communication strategies [54,55].

In the deployment of multiple agents for data collection missions, communication management is pivotal for mission integrity and autonomy [56]. Errors in the transfer of navigational or field sensor information could result in mission failure or a loss of UV agents depending on the application. A robust communication link is necessary to ensure the mission will be executed with minimal interruptions and full functionality [57,58]. Reliable multi-agent communication fosters a better ability to react and learn from the operational environment, and enables agents to adjust as required to achieve mission objectives.

Previous works in connectivity management have focused around managing intermediate mobile units between a primary mobile and a Base Station (BS) based on algebraic connectivity [59,60]. Other studies have worked on increasing the range and maintaining connectivity outside the BS range by the use of multiple robots to extend the link [61]. Hsieh et al. [62] focused on maintaining end-to-end communication by examining multiple agent's transmission to a BS and checking the bandwidth on the BS, while also using RSSI for connectivity. Examination of throughput by repeated transmission of an image versus signal strength is done in [63]. While in that study, the focus is the optimization of multiple units' positions; an effective end-to-end link management algorithm is needed. In order to understand what constitutes as a good communication link, metrics should be examined and compared for suitability as a Link Quality (LQ) assessment tool.

This paper aims to examine popular measures of connectivity and compare them based on Assessment Accuracy (AA) and Time To Process (TTP), which are essential in multi-agent robotic systems. It is worth noting that AA and TTP are inversely proportional, as accuracy tends to increase with more data points, but subsequently will require a longer processing time to make a decision. Henceforth, the best metric will provide an optimum balance between accuracy and TTP. In this context we define assessment accuracy as how well the system can correctly assess the current connectivity state it is in. Accuracy is a critical measure here as a poor assessment could lead to a UV leaving the connection zone and becoming lost. Time to process is representative of the total time the system needs to correctly judge the current connectivity state. Smaller times to process will reduce the time required to correct a deteriorating communication scenario and improve mission reliability.

The first objective of this paper was to provide a comprehensive study of LQ metrics, namely Received Signal Strength Indicator (RSSI), Packet Error Rate (PER), and Error Burstiness (EB) individually and then offer a comparison between each. In this study, RSSI is the relative received signal strength in a wireless environment, typically received as an analog value in arbitrary units. PER refers to a ratio, in percent, of the number of communication link packets not successfully received to the total number of packets sent. EB, in our application, was characterized by the amount of consecutive lost packets in a communication link. In this comprehensive study, EB has been shown to have a shorter TTP than the other metrics while maintaining similar assessment accuracy. It was found that the use of EB can predict the link quality in a shorter time and pre-emptively avoid a communication loss. To further examine how EB acts in a UV connection management scheme, an algorithm is developed. Finally, the feasibility of EB as a communication link metric is investigated by using an experimental UV communication link.

The remainder of the paper is organized as follows, Section 3.1 establishes a background, Section 3.2 details the experiments, Section 3.3 discusses results and analysis, and Section 3.4 contains concluding remarks.

3.1 Background

The publications summarized in the following subsections do offer insight into each of RSSI, PER, and EB but do not specifically compare them against each other.

3.1.2 Received Signal Strength Indicator

RSSI has been largely investigated on localization systems in an attempt to correlate distance to an RSSI value and develop a relationship between its value and the distance. Authors in [67] and [68] draw the conclusion that RSSI cannot be mapped accurately to a distance as there is too much variance. Further, RSSI values do not offer decimal accuracy in packet based communication systems, which constrain the distance resolution. Additional studies in [69,70,71] have developed correction schemes to mitigate inaccuracies in distance estimation by using RSSI values. However, improvements were small, these studies highlighted that the RSSI link based management systems could work in certain applications where accuracy is not the primary goal.

3.1.2 Packet Error Rate

PER as an LQ metric has been used in a number of different applications [72-76], where it was shown to be reliable to estimate LQ accurately. PER can also capture impact of interference, multi-path fading, and weather conditions. Furthermore reported in [77], the PER near the end of the reliable communication link showed time variance, this section of the communication link was defined as a grey zone because of its unpredictable LQ.

3.1.3 Error Burstiness

The examination of EB as a metric of LQ has been performed in [78]. Based on this work a number of errors were bursty in the grey zone, which means they fluctuate between good and bad LQ. Thus in [79], an algorithm to measure link EB was developed, which allowed the system to pause transmission, if the LQ was bad. Using EB as a metric allowed for the reduction of the average transmission cost by 15%. Wavelet analysis of RSSI in [36] showed that errors in wireless links are bursty in nature.

3.2 Examination of RSSI, PER, and EB at communication link limits

This section describes experimental studies of PER, RSSI and EB as potential LQ metrics for multi-agent UV deployments. The metrics were studied by changing the distance between the mobile agent and BS.

3.2.1 Methodology

For this study, the communication zones were labeled as good, average, and poor. PER was used in identifying these zones since it is generally believed to be the most reliable of these three metrics. In the good zone, PER is under 10%, and communication is very reliable. PER regions between 10% and 40% are considered average (i.e. grey zone), while anything higher than 40% PER is considered poor. The most important decision in mobile robotic applications is to identify the transition region from average to poor. In this region the LQ can change very rapidly and the mobile unit must make a rapid decision to maintain the communication link. Thus there is a paramount importance of having an accurate and fast LQ metric. Subsequently this study focused on developing such an LQ metric that can identify this transition region.

3.2.2 Packet Error Rate

PER was measured on a mobile agent by using received Acknowledgements (ACKs) from transmitted packets to the BS. To get an accurate PER measurement, the number of observed packets (window size) was critical. Equation (1) describes how PER was obtained in the experiments. Loss of ACKs as well as erroneously received ACKs constitute error packets and were included in the PER calculations. While PER is an effective LQ estimator, the accuracy of PER depends on observation period, namely window size. This is illustrated in Figs. 3.1 and 3.2, where Fig. 3.1 shows that a short window size of 4 packets can drastically alter the PER metric and may not properly realize LQ changes in fast moving flying robot network. When the window size is large enough, accuracy of the PER metric increases and stabilizes, and allows it to be useful in an accurate decision making algorithm. However, this increased window size increases decision making time, this lag can be problematic when it is required to make fast LQ assessments. When the mobile agent discovers that the LQ is deteriorating, it may be too late to reverse course to a better communication region. Fig. 3.2 illustrates how PER changes with varying window sizes in a grey zone. Two different window sizes were tried, labeled as W=5 and W=20. In this region, LQ varies drastically because of a greater likelihood of errors.

$$PER = \frac{(Packets\ Sent - Recieved\ ACKs)}{Packets\ Sent} \times 100 \quad (1)$$

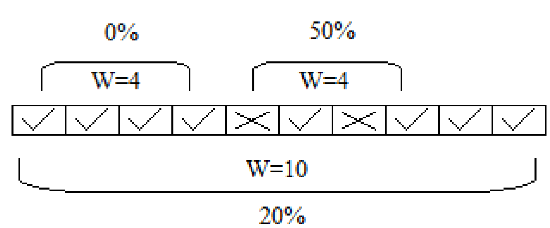

Fig. 3.1 A smaller window size provides a unstable PER reading, while a larger window provides a much more accurate reading at the expense of more time.

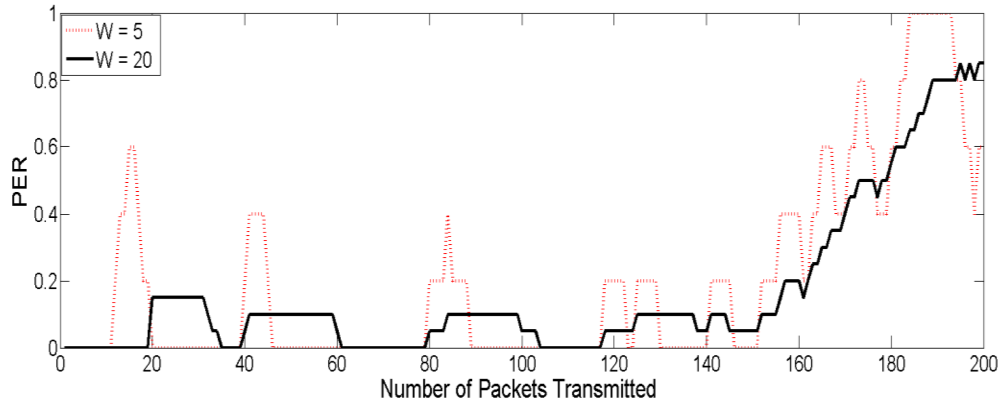

Fig. 3.2 A window size of 5 shows a much larger PER then a window size of 20, where W=20 shows a much more stable PER

Based on our early tests, each experiment was run for a window size of 200 packets to provide a clearer characterization of the metric for this application. Fig. 3.3 provides PER values vs. distances. As the distance increases between mobile agent and the BS, PER gets increases and becomes less predictable, which is illustrated with confidence intervals from five repeated experiments. In our experiments, it was observed that after 27 meters separation between the mobile and the BS, PER became unreliable.

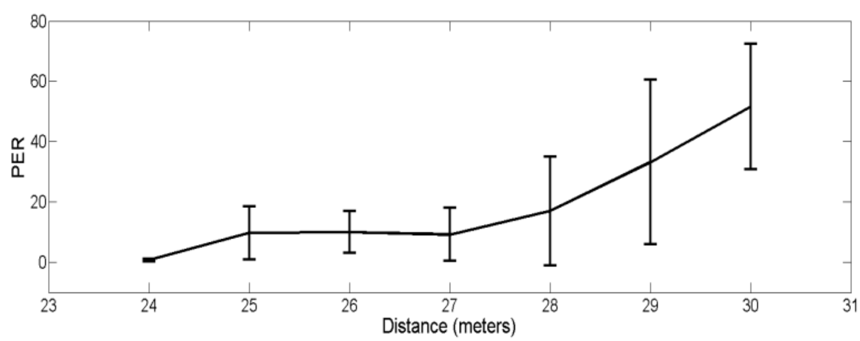

Fig. 3.3 Packet Error Rate versus Distance

3.2.3 RSSI

Most of the modern radio receivers provide RSSI values for each packet. This can be retrieved using hardware control application program interfaces. In the experiments, an average RSSI value was calculated using (2).

$$RSSI = \frac{(\sum_{i=1}^{n} nPacketRSSI)}{n} \quad n = total\ \#\ of\ packets \tag{2}$$

Fig. 3.4 illustrates RSSI values vs. distance, where increased distance decreases received signal power. In addition to this, the figure shows the natural instability of RSSI values due to multi-path fading. This suggests that RSSI may not be the best LQ metric in packet communication networks. However RSSI can be valuable as a secondary metric to help confirm estimations made by other LQ metrics.

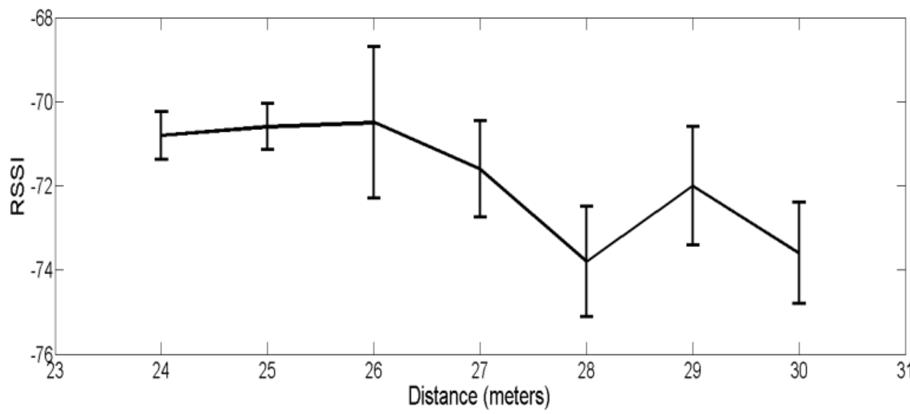

Fig. 3.4 RSSI versus Distance.

3.2.4 Error Burstiness

EB can be visualized by using Fig. 3.5. The EB metric is calculated by counting consecutive packet losses, which is done by counting missed ACKs as well as timeouts. Large consecutive losses indicate an unreliable communication link which makes EB a good candidate as a viable LQ metric. EB studied in [33] concluded that errors in links tend to occur in bursts rather than as singular stochastic events.

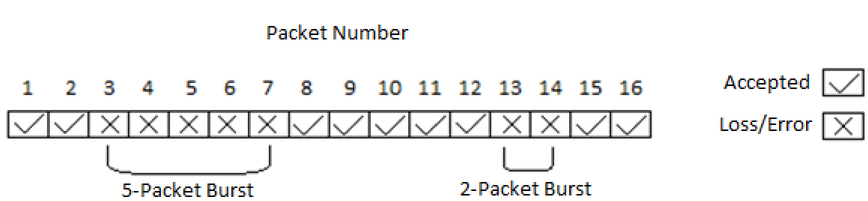

Fig. 3.5. In this examination of 16 transmitted packets two separate bursts are illustrated.

Table I provides the EB counting algorithm used in this study. The counting process examines the current packet versus the last packet and checks to see if they have both failed. Continuous failures increase the burst counter, while continuous successes are not counted. Moving from a lost packet to a success resets the counter and saves the burst value. Conversely, moving from a successful packet to a lost packet initializes the burst counter. This algorithm is used to count consecutive errors in a stream of packets. In order to examine EB, in the experiments, the three largest error burst counts were stored. This allowed us to examine and identify bursts, and later develop the LQ management algorithm based on EB.

TABLE 3-1
Error burstiness counting algorithm

Last Packet	Current Packet	Outcome
✓	✓	Do nothing
✗	✓	Save last EB counter and reset
✓	✗	Initialize new EB counter
✗	✗	Increase EB counter

Figs. 3.6, 3.7, and 3.8 show that the number of consecutive losses are influenced by increasing distance. Data was collected on a mobile agent at an initial distance of 24 meters (m) from the BS since distances shorter than 24 m did not have connectivity issues. Measurements were then taken every meter thereafter until PER reached 50%. A stream of 200 packets was transmitted at each distance, the mobile agent remained stationary and the packet stream was recorded. These experiments were then repeated five times for each distance, averages of these experiments and variations were reported in Figs. 3.6, 3.7, 3.8. The first three largest error bursts were recorded after receiving 200 packets, this allowed for a better understanding of the EB metric. A large initial EB was followed by proportionally larger secondary and tertiary bursts. This demonstrates that a large burst can lead to additional bursts, which can be detrimental to LQ. Similarly to

PER, the farther the mobile agent moves from the BS the larger the increase in consecutive errors.

Another observation was that in a grey zone where connectivity issues arise, no hard-line guarantees can be made for LQ. Predictions for LQ become less accurate and unstable the farther the mobile agent moves in an unreliable connection. In mobile agent robotics, it is important to identify LQ issues as fast as possible because the agent can quickly move into a less reliable link region. Once in such a region, re-connection could pose an issue.

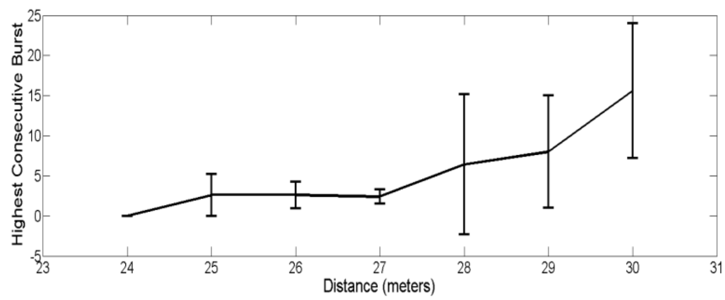

Fig. 3.6 The highest consecutive loss is graphed against distance.

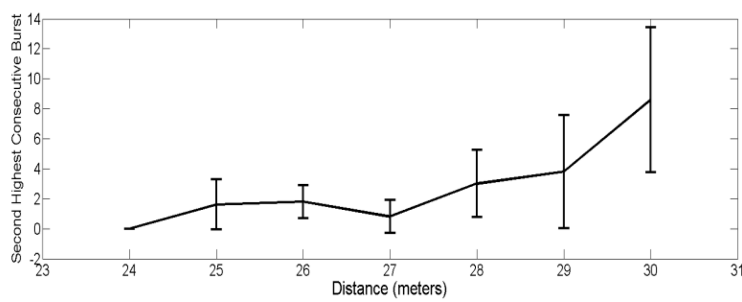

Fig. 3.7 The second highest consecutive loss is graphed against distance.

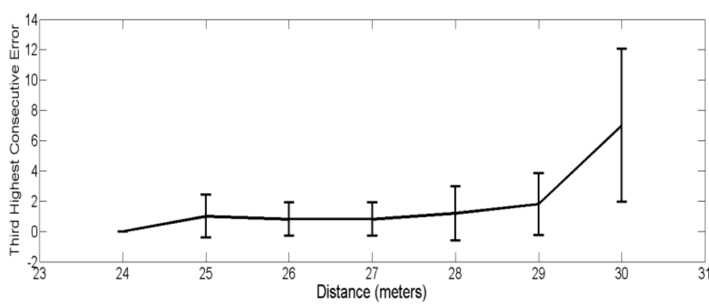

Fig. 3.8 The third highest consecutive loss is graphed against distance.

3.2.5 Error Burstiness in Correlation to Packet Error Rate

Analysis of Fig. 3.3 versus Figs. 3.6, 3.7, 3.8 shows that good correlations exist between PER and EB metrics. Goodness of fit between EB and PER is determined from the experiments. Goodness of fit values for PER and EB are 0.967, 0.945, 0.850 for results presented in Figs. 3.9, 3.10, and 3.11. This close fit between EB and PER can be exploited in link connection management by using EB as the LQ metric.

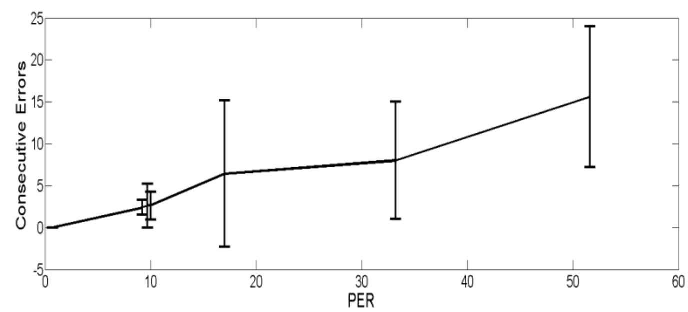

Fig. 3.9 Burstiness versus Packet Error Rate R^2=.967

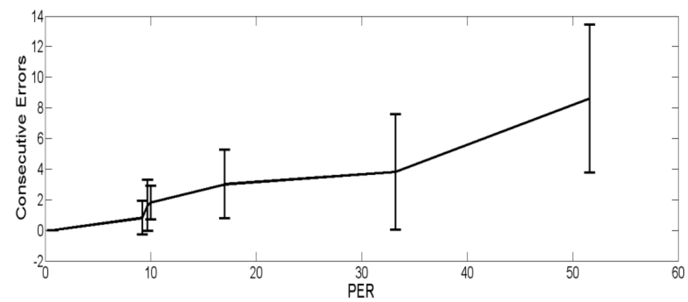

Fig. 3.10 Burstiness versus Packet Error Rate R^2=.945

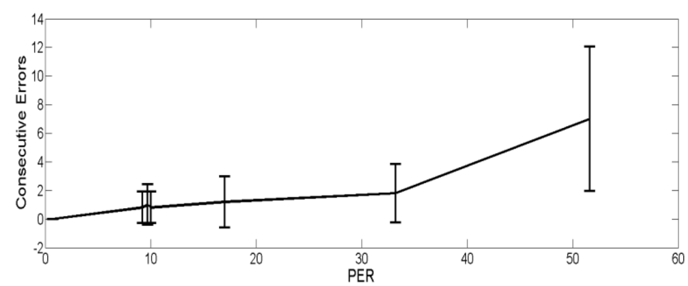

Fig. 3.11 Burstiness versus Packet Error Rate R^2=.850

EB can determine deterioration in the link faster than the PER metric since it can assess link quality based on a smaller amount of packets. This leads to faster decision making to mitigate the loss of communication connection between units. Fig. 3.12 is provided to help illustrate EB's temporal advantage in LQ decision making. The decision making time if PER is used is $(T_x + T_{ACK}) * W$, where W is window size, T_x is transmission time, and T_{ACK} is the ACK time as given in (3). However, if EB is used, the time is $(T_x + T_{ACK}) * threshold_{EB}$, where $threshold_{EB}$ is the maximum consecutive errors, as given in (4). Since $W \gg threshold_{EB}$, then the decision making time is reduced significantly.

$$T_{Decision\_PER} = (T_x + T_{ACK}) * W_{Size} \tag{3}$$

$$T_{Decision\_EB} = (T_x + T_{ACK}) * threshold_{EB} \tag{4}$$

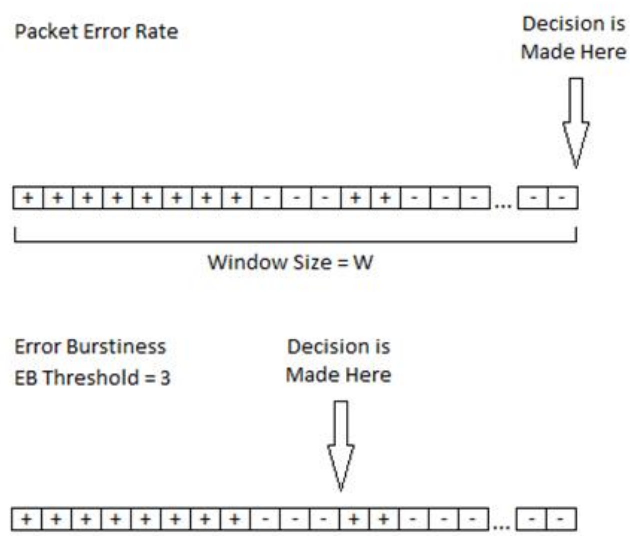

Fig. 3.12 Visualization of the Decision Making Process

3.3 Error Burstiness Based Connectivity Management

In this section, an EB based LQ metric and connection management algorithm for mobile robot networks is developed and investigated. In the previous section, we identified that there is a strong correlation between EB and PER metrics. Although PER has been shown to be a reliable LQ metric, obtaining a stable PER requires a larger TTP than EB. Hence it delays the decision making in the connection management algorithm. Replacing PER with EB will allow a mobile robot network to measure LQ faster. In order to test and verify the effectiveness of EB metric, an experimental network consisting of a BS and a mobile robot receiver were constructed using off-the-shelf hardware. In the experiments, EB and PER metrics were both utilized in the LQ management process.

3.3.1 Design of EB Experiments

Two experiments were developed to test the effectiveness of EB metric for LQ assessment in an open field. In the first experiment, the vehicle would travel along a straight line until a preprogrammed EB threshold value was reached, then stop. Three different thresholds of 5, 7 and 10 consecutive errors were chosen, then the experiment was repeated 10 times for each threshold. The vehicle's electronic controller was triggered to stop the vehicle when the EB count exceeded the predetermined EB threshold. Once the vehicle stopped, the distance between vehicle and BS was measured. The algorithm and experimental setup can be seen in Figs. 3.13 and 3.14. The second experiment was developed to investigate the symmetry of the EB metric to assess its sensitivity to direction.

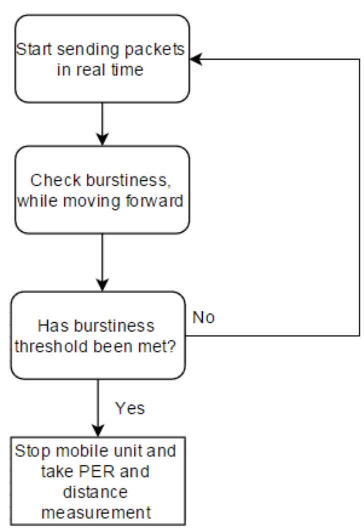

Fig. 3.13 The procedure followed to collect data.

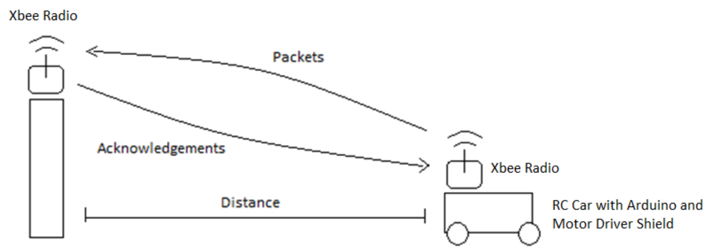

Fig. 3.14 Visualization of the Experimental Setup.

3.3.2 Hardware

The two nodes in the system were referred to as the BS; which was stationary and the other was the mobile agent. Two Xbee Series 1 radios operating with the IEEE 802.15.4 standard were used for communications [80]. Transmit power was set to 1 milli Watt (mW) and the receiver sensitivity was -92 dBm. Communication range was listed in the datasheet of the radios up to 90 meters in an open field. The operating frequency is in the Industrial Scientific and Measurement (ISM) band of 2.4GHz. Whip antennae with 1.5 dBi were used in all the experiments. The BS was a laptop with an Xbee radio attached through USB. The BS was programmed to receive packets from the mobile agent and to send ACKs back. The mobile agent was a re-configured remote control car, where an Arduino board with ATmega1280 microcontroller [81] was programmed to send packets to the BS. The EB based LQ metric was implemented on the Arduino board to control the movement of the vehicle.

3.3.3 Experimental Results

The first experiment was designed to evaluate effectiveness of an EB based LQ metric in a link management routine. In this experiment, the vehicle moved in a linear line from the BS through a given angle heading and a threshold EB value. The vehicle was programmed to move forward while continuously transmitting data packets and receiving ACKs from the BS. The vehicle stopped when the pre-programmed EB threshold was reached. These experiments were repeated 10 times for each threshold value. The selected thresholds were 5, 7 and 10 error counts. The results are provided in Table II, where results were gathered based on the EB threshold selected. These experiments revealed that the EB based LQ metric consistently provided the same distance with small deviation, which are between 1.09 to 2.09 meters. This suggests that

EB may be a good candidate as an accurate link management parameter. Stopping locations of the vehicle are illustrated in Fig. 3.15 to provide a better perspective of the experimental results.

TABLE 3-2
Experimental results for different error bursts

	Average Stopping Distance (m)	Distance Standard Deviation (m)	Average PER	PER Standard Deviation
5 Errors	24.57	1.09	30.85	27.21
7 Errors	29.64	2.09	48.51	24.73
10 Errors	37.05	2.08	85.49	16.88

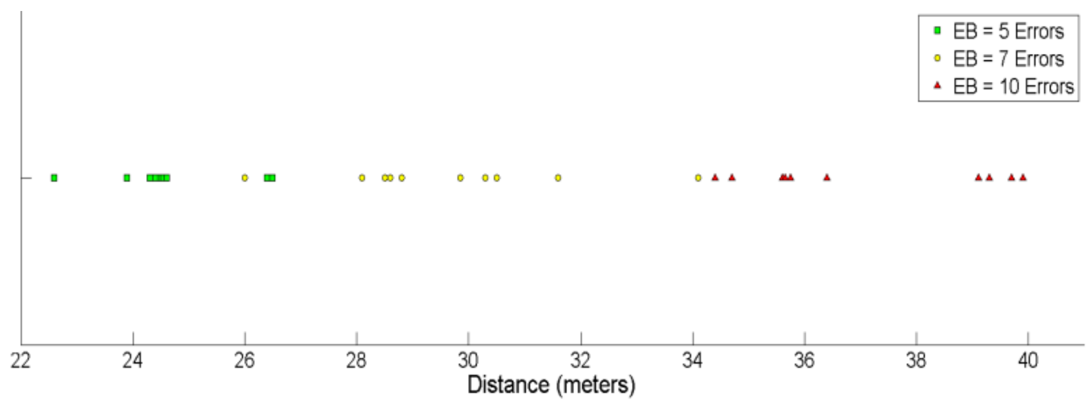

Fig. 3.15 Experimental Results

From these experiments, it is observed that each EB threshold corresponds with a different average stopping distance and PER. As the EB threshold increases, so do the distances travelled by the vehicle and PER. The unreliability of a grey (communication) zone can be clearly observed as PER standard deviations are high. Nonetheless, each EB threshold stays within a certain PER range, and lowering the EB threshold lowers the overall PER. Segments in the transition from different EB thresholds will have a slight overlap area, this can be best seen in Fig. 3.15 at around 26 meters.

TABLE 3-3
Experimental results for EB in different directions

	Average Stopping Distance (m)	Distance Deviation (m)	Average PER	PER Deviation
East	28.69	1.94	32.04	22.44
West	28.80	2.99	25.30	10.05

The second experiment was conducted to verify symmetry around the BS. In this scenario, the EB threshold was set to 5 consecutive errors. Results are provided in Table 3-3 and stopping positions can be seen in Fig. 3.16. In these experiments, the average stopping distance in the east was 28.69 m with a standard deviation of 1.94 m; and in the west direction, it was 28.8 m with a standard deviation of 2.99 m. These experiments verified that average stopping distances in both directions were comparable and deviations were rather consistent. However, the PER values had a wider gap and were relatively less consistent. This inconsistency in PER can be attributed to time variation in the wireless channel due to multi-path fading. These experimental results were repeated in subsequent scenarios and a number of trials were conducted during the algorithm development phase.

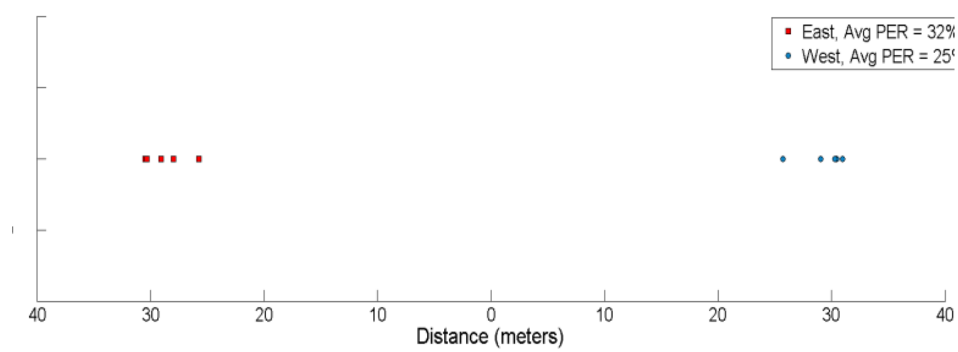

Fig 3.16 Visualization of 5 consecutive error stopping distances to test out boundaries in two directions.

3.4 Conclusion

In this paper, an EB based LQ metric was evaluated to potentially reduce the delays and complexity associated with PER based LQ metrics. Results of experiments suggest that EB has advantages as a LQ metric in mobile robot communication systems. Most notably, using EB provided better communication link assessment accuracy than using PER. Of equal importance the time to process is shorter than PER. Both of these advantages are essential in maintaining critical communication links in fast moving multi agent networks.

Future work includes improving the link management algorithm developed here and increasing understanding of how bursts occur and how to manipulate that data to give a real-time realization of the communication link.

CHAPTER 4
COMMUNICATION LINK PERCEPTION FOR MOBILE AGENTS

Through the identification of PER and EB as capable LQ metrics in the previous chapter, this section looks to expand and develop an algorithm by combining their strengths. The advantages of PER are its ability to give an overall good estimation of the LQ by comparing the amount of lost packet to successful ones. A large PER demonstrates that the communication link is facing issues. The leading concern with using PER is the selection of the sample size, this sample size will be referred to as window size in this work. PER is calculated as a moving average to bring the decision making time as close to real-time processing as possible. Furthermore the algorithm will scan for sudden EBs as consecutive losses are disastrous to LQ. The probability of high EB increases with a higher PER, therefore scanning for EB can save the link faster.

4.1 PER Metric

PER in this paper was incorporated on a moving mobile agent, which would send continuous packets to a BS and receive acknowledgements (ACKS) in return. This platform was created to simulate a realistic communication system that can help further develop communications perception in UV schemes. PER is the ratio of lost packets to the number of transmitted packets. Both lost and error containing packets are considered in our PER calculations as they both cause detriment to the LQ and both should be minimized. The amount of packets to transmit and be used to calculate PER is determined by the window size. Window size is chosen based on the necessary decision making time. A larger window size leads to increased accuracy of the system but at the burden of processing time. The determination of the proper window size is done by first identifying T_{Total_Avg} , which is the time it takes to transmit a packet noted as T_x and the time it takes to receive an ACK noted as T_{ACK} in (4). Decision making time is $T_{Decision\ Making}$, which is just the product of T_{Total_Avg} and window size noted as W_{Size}

in (5). Window size can then be determined by dividing the required decision making time by the average time to transmit and receive an acknowledgement as in (6).

$$T_{Total\_Avg} = (T_x + T_{ACK}) \quad (4)$$

$$T_{Decision\ Making} = (\ T_{Total\_Avg} * \ \ W_{Size}) \quad (5)$$

$$W_{Size} = \frac{T_{Decision\ Making}}{T_{Total\_Avg}} \quad (6)$$

In the case of our experiments a $T_{Decision\ Making}$ of one second was considered satisfactory for the speed the mobile unit was travelling at. The T_{Total_Avg} for the XBEE Series 1 radios used was 50ms, which lead to a the decision of using a W_{Size} of 20.

4.2 EB Metric

EB examines consecutive lost packets for the determination of the LQ, as larger consecutive bursts are more likely to cause disruption in the communication process. While PER can offer a wider scope and view of the LQ, EB can offer an even faster response and awareness of communication problems. EB can also give additional insignt of LQ where PER wouldnt as seen in Fig 4.1, where approved packets are noted as + and lost packets are noted as -.

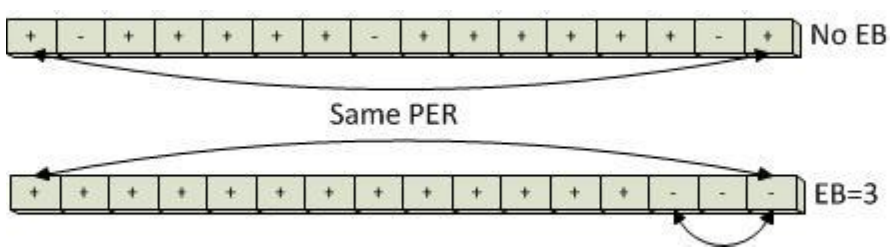

Fig. 4.1. Two different data streams with the same PER but with different EBs

EB can be implemented to a system by determining the threshold the communication link can allow and provide a faster response to save the communication link. Once the EB threshold is reached the algorithm can raise a flag and stop the mobile agent from continuing on the detrimental path. The time to reach this decision (T_{EB})can be seen in (7), where $threshold_{EB}$ is the EB threshold as determined.

$$T_{EB} = T_{Total\_Avg} * threshold_{EB} \quad (7)$$

4.3 Integration of PER and EB for the Development of a Communication Perceptive Algorithm for UVs.

4.3.1 Methodology

A mobile agent was programmed to drive away from a BS while continuously transmitting packets and receiving ACKS, until one thousand were sent. This experiment was repeated ten times and packet data was recorded in real-time. The testing area was done in a large parking lot with no major obstacles or obstructions, therefore the major loss of communication was due to path-loss effects. This experiment allows access to see how LQ responds in real-time environment and will allow for the development of a practical solution to the development of communication perception for UVs.

4.3.2 Link Quality Classification from Results

A moving average window of size of 20 was used in measuring the PER of a moving mobile away from a BS. The window size was chosen of 20 was chosen as one second memory and response time was sufficient for our vehicle speed. The average of the eight experiment runs is plotted in Fig 2. PER is shown to increase with distance from the BS due to path-loss effects. Conversely some areas see reduction in overall PER, as the LQ recovers after some distance due to multi-path fading. A communication system therefore cannot always be limited by range as you may lose on spatial sensory range. Furthermore, a communication perceptive system should be as dynamic and flexible as wireless communications tend to be unpredictable at times.   Figure 4.2 can be split up into three major regions which we classify as good, tolerable and unstable. Good regions are areas of zero PER, tolerable regions are areas under .10 PER and unstable regions are anything passed .10. The rationale behind choosing .10 PER as the changing point is that anything above that value is much more violate.

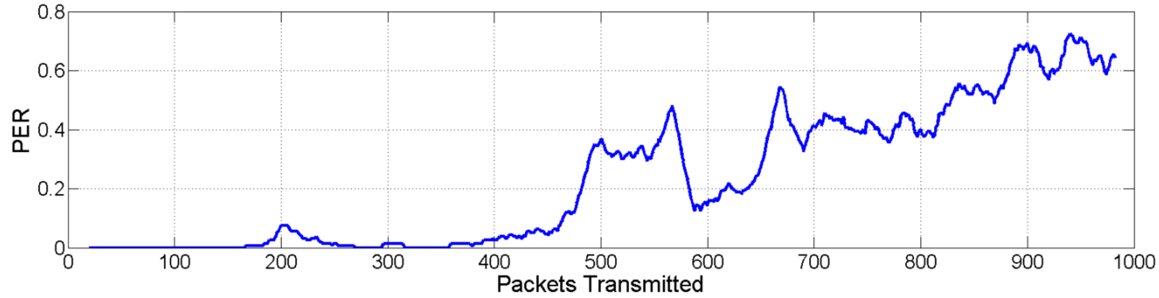

Fig. 4.2. Moving PER with a window size of 20

Figure 4.3 displays the probability of two consecutive errors occurring in the data stream. The data was collected by using (8); where P_{2EB} is the probability two consecutive error bursts, $P_{loss(current\ packet)}$ is the probability of loss of the current packet, and $P_{loss(last\ packet)}$ is the probability of the last packet.

$$P_{2EB} = P_{loss(current\ packet)} * P_{loss(last\ packet)} \tag{8}$$

Consecutive errors of size two are never found in good areas of connectivity, and only sparticaly found in tolerbale areas. Areas of unstable connection and with higher PER are more likely to find a higher probability of consecutive errors.

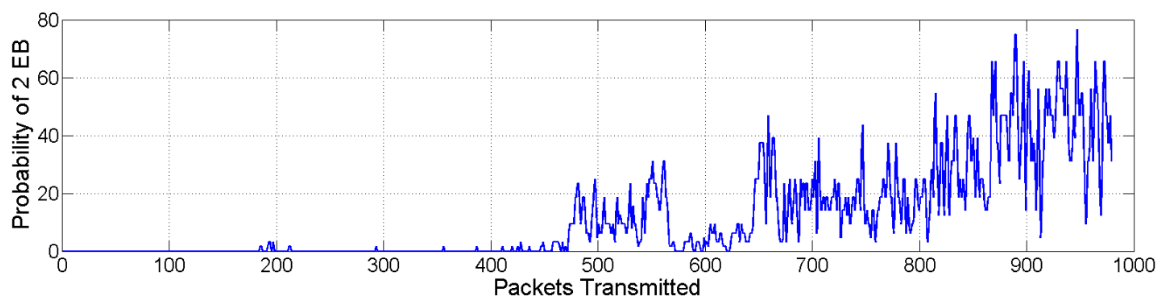

Fig. 4.3 Probability of two consecutive errors occurring

Figure 4.4 visualizes the probability of five consecutive errors occurring in a packet stream from a moving mobile agent and it is based off (9). EB of magnitude 5 occur primarily when the system is in the unstable region.

$$i = current\ packet\ postion\ \ P_{5EB} = P_{loss(i)} * P_{loss(i-1)} * P_{loss(i-2)} * P_{loss(i-3)} * P_{loss(i-4)} \tag{9}$$

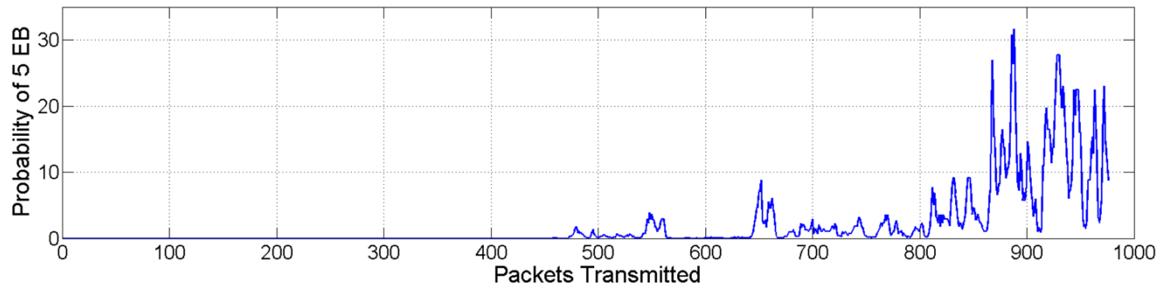

Fig. 4.4. Probability of five consecutive errors occurring

4.3.3 Development and Implementation of Communication Aware Algorithm

The following section develops an algorithm that allows a mobile agent to understand its LQ by examining its current PER and EB values and by labeling the LQ as either good, tolerable, or unstable. This allows for the advancement of autonomy in UV communications as each agent is capable of perceiving its own LQ. Knowledge of the communication link allows for correction and possible avoidance of communication loss.

Good LQ can be classified as an area of 0 PER and 0 EB, which provide a steady and stable communication link. This is the ideal scenario in most UV missions to guarantee mission effectiveness and stable communication. The algorithm developed is displayed in TABLE 4-1, where a tolerable LQ is defined as an area of equal to or under .10 PER and with an EB no greater than one; in this situation the link is starting to lose packets and have some communication issues. Navigational and important data can be lost so correcting the link at this point is essential for mission robustness. For certain non-real time critical mission this area may be acceptable if the agent is collecting data and it is capable of controlling its own navigation. An unstable LQ is classified as an area of over .10 PER or an EB of equal to or greater than two. The combination of a moving window PER and EB checking allows for the individual agent to understand its LQ. The process can be seen in Fig 4.5 where the two sub processes are working at the same time.

TABLE 4-1
Algorithm

PER	EB	Result
0	0	Good LQ
<=.10	EB<2	Tolerable
>.10	N/A	Unstable
N/A	EB>=2	Unstable

An experimental setup was designed to test out this algorithm by implementing it on a mobile agent to test the boundary conditions. The agent was initially placed in a region of good LQ and left to drive until an unstable condition was met, upon reaching this condition the agent would reverse in the opposite direction and return to an area of good LQ. This was repeated until at least four recoveries were made and this was called one event. The throughput was recorded for each event and was repeated ten times. The average throughput of all the events was 75.4%. Improvement to this throughput was made by changing the boundary condition from unstable to tolerable, which provided an average throughput of 86.3%

TABLE 4-2
Final Results

Throughput	Deviation	Condition
86.3%	5.4	Tolerable
75.3%	4.9	Unstable

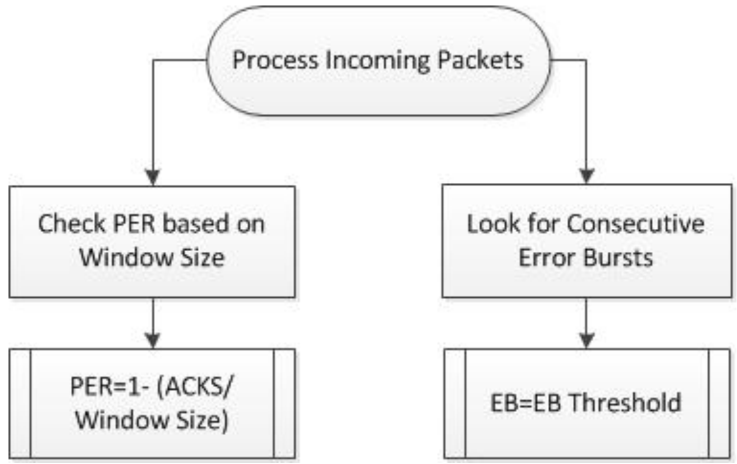

Fig. 4.5. Both processes occurring concurrently

4.3.4 Flexibility of Different Window Sizes

A robust and efficient communication perceptive system should be capable of working with different radios that have different transmission speeds, as no one UV system uses the same hardware therefore flexibility of the algorithm is vital. The main advantage of this system is the flexibility EB provides and allows the algorithm to work with different window sizes. Consequently the use of only PER limits the system when window sizes are too small or too large. In system with a small window size of 5 examining for PER is impractical as sample size is too small and the PER will fluctuate rapidly, in this scenario an examination of the EB threshold would be much more practical and avoid over correction of the system. A large window size of 100 may gather too much information and may lead to skewed PER results, thus examination of EB threshold can flag the system faster and warn of a potential communication problem.

4.4 Conclusions

In this section a PER and EB hybrid algorithm was created. This was accomplished by firstly optimizing the window size for the hardware used. In addition, PER tests were conducted using a moving average with the optimized window size to bring the system to real-time. Furthermore, probability of different bursts occurring were illustrated. Through this analysis three areas were defined as good, tolerable, and unstable. Finally boundary conditions were developed through the experimental data. The system described in this work allows for the agent to have communication link awareness and allow it to correct its own link. Further work needs to be focused around the development of a more robust mobile agent with better stopping accuracy and improved moving efficiency.

CHAPTER 5

CONCLUSIONS

In this thesis, it was demonstrated that communication is of great importance in multi-agent systems. This was proven through the examination of the different communication structures and formation control where communication was shown to be critical in all aspects of these applications. Popular hardware was identified by examining current multi-agent sensor networks while exploring their successes and failures. Subsequently a study was done on three metrics: PER, EB, and RSSI, where each was tested at different distances from a BS. PER and EB showed signs of linearity and were further studied. An algorithm was developed that combined both PER and EB which allowed an understanding of the LQ by classifying it in three sections. This work allows for further improvements to be made to multi-agent systems by offering a flexible communication perceptive algorithm that can be implement on a variety of different platforms. Further work needs to be done in connecting a more robust control and navigation system to the communication system. Different features such as GPS can be used to provide previous positional LQ values for the development of LQ memory.

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