

AN ENERGY-EFFICIENT TRANSMISSION POWER CONTROL PROTOCOL FOR  
COOPERATIVE ROBOTICS

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COOPERATIVE ROBOTICS

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A Thesis

Submitted to

the Graduate Faculty of

Auburn University

in Partial Fulfillment of the

Requirements for the

Degree of

Master of Science

Auburn, Alabama  
December 19, 2008

AN ENERGY-EFFICIENT TRANSMISSION POWER CONTROL PROTOCOL FOR  
COOPERATIVE ROBOTICS

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## VITA

Arthi Kothandaraman, daughter of A. Kothandaraman and S. Lavanya Veena, was born on October 11<sup>th</sup>, 1984, in Madras, India. She entered Anna University in June 2002, and graduated First Class with a Bachelor of Engineering degree in Electronics and Communication Engineering in May 2006. In August 2006, she began working towards a Master of Science degree in the Department of Electrical and Computer Engineering at Auburn University.

THESIS ABSTRACT

AN ENERGY-EFFICIENT TRANSMISSION POWER CONTROL PROTOCOL FOR  
COOPERATIVE ROBOTICS

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Master of Science, December 19, 2008  
(B.E., Anna University, 2006)

63 Typed Pages

Directed by Thaddeus Roppel

Severe energy constraints inherent in multi-robot networks dictate that communication be performed as efficiently as possible to enable longer network lifetime and successful task execution. Therefore, energy-aware communication protocols are necessary for network longevity. A number of energy-oriented protocols for mobile ad-hoc networks (MANETs) are proposed in the literature. However, the computational intensity and generic nature of these protocols render them unsuitable for cooperative robotic networks. In this thesis, a Transmission Power Control Protocol (TPCP) to enhance the energy efficiency and network lifetime of an IEEE 802.11g-based cooperative robotic ad-hoc network is presented. The proposed protocol varies the transmission range of a node to exclusively accommodate an independent node's neighbor set. Such a scheme is simple, preserves connectivity, and allows low power transmissions. Simulations were performed to compare the energy consumption of the network with the conventional fixed transmission range and TPCP approaches.

Simulation results indicate that the proposed algorithm increases network lifetime by more than 20%.

## ACKNOWLEDGMENTS

I am deeply indebted to Dr. Roppel for his time, advice, understanding and patient encouragement through the winding journey towards this thesis. I owe many thanks to Dr. Agrawal, Dr. Wentworth and Dr. Mao for their guidance and acceptance to serve on my thesis committee. I would like to express my heartfelt gratitude to all the people who have made the completion of this thesis possible: Chris Wilson, for the long hours he spent in bringing me up to speed on the CRR SARA project. Yogesh Kondareddy, for his invaluable pointers on the technical aspects of this work. Sandeep Neeli, for being there for me through it all. My family, for their unwavering faith in me and for their steadfast support in all my endeavors. And last, but never the least, a final word of thanks to the Almighty for guiding me thus far.

Style manual or journal used Institute of Electrical and Electronic Engineers  
Journal Style (together with the style known as “aums”).

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Computer software used MATLAB 7.0, Microsoft Word 2003, L<sup>A</sup>T<sub>E</sub>X.

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## CHAPTER 1

### INTRODUCTION

The past few decades have seen a sea change in the way telecommunications takes place. Advancement of wireless communications, coupled with the evolution of sensor technology, has aided the growth of a new field of robotics research termed as mobile robotics. Mobile robots have a plethora of applications ranging from lunar sample collection [17] to carpet cleaning [21]. Of these, multi-robot exploration of unknown environments is a very interesting field of research. Such multi-agent systems not only speed-up complex tasks, but also increase robustness and eliminate single-point failures.

A recent development in mobile robotics is that of *teams of autonomous robots* collaborating to accomplish a pre-determined task. Such a network of autonomous robotic nodes is referred to as a *collaborative* or *cooperative robotic network*. These autonomous robot networks might be deployed for tasks that vary in complexity and dangerousness from simple surveillance or target location to building composite systems or traversing landmines. This thesis focuses on search and rescue operations by a multi-agent robot network.

The dictionary defines *collaboration* as two or more entities working together with a common objective, while sharing information and aiding each other in achieving the common end goal. Often, collaborative endeavors of distributed systems prove to be more successful and satisfactory than dedicated purpose-oriented attempts of

centralized systems with little or no information exchange [20]. This makes cooperating multi-robot systems a popular choice for exploratory applications such as military reconnaissance [11] or search and rescue operations [12]. Cooperative robot networks offer the possibility to handle diverse capability. The inherent system redundancy in multi-agent network increases their robustness, and their potential for parallel task execution paves way for superior performance. The design of such multi-robot systems is not a trivial task because there are many trade-offs involved in the final design solution.

Efficient, reliable communication is one such significant component of a good cooperative robot network because exchange of information is essential to the success of collaborative missions. Search and rescue operations on an unknown terrain that may or may not have a communication infrastructure call for a network *on-the-fly* or a *mobile ad-hoc network* (MANET). In an autonomous robot network, the deployed robots form an ad-hoc network among themselves. Each robot in the network acts both as a host and a router, performing information processing as well as forwarding information. Such robotic nodes usually have severely restricted power supply and communication bandwidth. Therefore, *energy awareness* becomes a necessary feature in any communication protocol considered for such networks.

There has been extensive research on the topic of energy-aware protocols for communication over MANETs in recent times. Nevertheless, the protocols proposed in the literature fail to take into account the special properties of a multi-robot network such as cooperative communication and potentially predictable mobility. Moreover, the proposed protocols tend to overhaul entire chunks of existing infrastructure or are highly complex to implement. Such implementation is neither practical nor feasible in

a mobile robotic node where there is constant tug-of-war between power resources allocated for task execution and communication. Another unacceptable tradeoff made in typical power-efficient protocols is network connectivity. In a cooperative robot network that might span a wide area, connectivity of nodes is crucial to successful task completion. In order to meet the unique requirements of a cooperative robot network, this thesis presents a simple energy-efficient Transmission Power Control Protocol (TPCP) to improve the network lifetime, while maintaining the connectivity in an IEEE 802.11g-based ad-hoc cooperative robot network.

The remainder of this thesis is organized as follows: Chapter Two gives an overview of communication in cooperative robotic networks. The TPCP algorithm is described in Chapter Three. Chapter Four discusses the experiments performed and the results obtained. A summary of the thesis, conclusions, and suggestions for future work are presented in Chapter Five.

## CHAPTER 2

### LITERATURE REVIEW

“...cooperative mobile robotic systems have the potential for reducing the need for human presence in dangerous applications” [30]

“...multiple-robot systems can accomplish tasks that no single robot can accomplish, since ultimately a single robot, no matter how capable, is spatially limited.” [5]

#### **2.1 Communication in Cooperative Robotic Networks**

A cooperative robotic communication network is one in which a team of robots perform locally optimal actions and collaborate via information exchange to arrive at a globally optimal task completion state. In [23], the authors experimentally demonstrate that task-sharing improves performance significantly. A simple box-pushing task that is difficult for a single robot becomes relatively easier for two autonomous cooperating robots equipped with sensing, control and communication behaviors. [24] explores cooperative communication in the context of robot exploration. The authors define cooperative communication in terms of improving quality of wireless communication in the network. They present a comparison of average power consumption in



a standard and a cooperative wireless network of robots and suggest that cooperating networks might in fact, have better network performance.

Cao et al [5] characterize three major types of robotic interaction, namely, interaction via environment, sensing and communications. Robotic communication is typically categorized as explicit or implicit [29]. Implicit communication is usually the result of an individual robot's perception of its environment. Explicit communication on the other hand, is the effect of deliberate transmission and reception of information over a communication network. Explicit communication relies on an underlying wireless communication mechanism [35] such as the IEEE 802.11 family of wireless local area network (WLAN) standards [27].

### **2.1.1 Inter-robot communication issues**

In the early days of robotics research, wireless communication on robots consisted of infrared (IR) technology owing to its low cost. Infrared systems were plagued by several deficiencies such as poor communication rate and quality (rain effect), short communication range and inability to pass through obstacles. A more preferred communication mobile robot communication design involves Radio Frequency (RF) technology, using which robots can communicate over point-to-point wireless links or broadcast over the entire network. The frequency hop spread spectrum (FHSS) and direct sequence spread spectrum (DSSS) modulation technologies are utilized at the license-free Industrial Scientific Medical (ISM) band (2.4 GHz). The advent of Internet-like networks has incited researchers to explore wireless LAN (IEEE 802.11), Bluetooth standards, and ad-hoc networking mode in mobile robot systems [41].

Wang et al.[41] discuss the relative merits of ad-hoc networking for mobile robots and analyze some performance metrics. Multiple mobile robots deployed for distributed sensing and exploration would typically have low power wireless transceivers whose range is only sufficient to allow direct communication with their immediate neighbors. This means that the information packet would need to traverse multiple hops before reaching its destination. Also, a single centralized point of control leads to poor fault tolerance and low robustness. Infrastructure for a mobile communication system might be unavailable or destroyed in the unpredictable and unknown environment that the mobile robots are deployed in. These constraints render multi-hop ad-hoc networks the obvious choice for collaborative mobile robots.

### 2.1.2 Mobile ad-hoc networks

A mobile ad-hoc network (MANET) is an autonomous collection of wireless mobile nodes that communicate over bandwidth-constrained wireless links. The network is decentralized and all network activity including topology discovery and message delivery must be executed by the nodes themselves. The distinctive features of a MANET are:

**Autonomous mobile terminal** Each mobile terminal in a MANET has basic processing capabilities like a host, but it can also perform switching functions as a router.

**Distributed operation** In the absence of an infrastructure for the central control of the network operations, the control and management of the network is distributed among the terminals.

**Multihop routing** In a MANET, data packets can be delivered from a distant source to the appropriate destination even when the destination is out of the direct wireless transmission range of the source. The data packets are forwarded from source to destination via one or more intermediate nodes which are also a part of the network.

**Dynamic network topology** The mobility of nodes in a MANET may cause the network topology and connectivity to change rapidly and unpredictably with time. MANET should adapt to the traffic conditions as well as the mobility patterns of the mobile nodes. The mobile nodes in the network dynamically establish routing among themselves as they move about, forming their own network on the fly.

**Fluctuating link capacity** The relatively high bit-error rates of wireless links might be more profound in a MANET. The wireless channel over which the nodes communicate is subject to noise, fading, and interference, and has less bandwidth than a wired network.

**Light-weight terminals** In general, the nodes in a MANET are mobile devices with little CPU processing capability, small memory size, and low power capacity. Such devices need optimized algorithms and mechanisms that implement the computing and communicating functions without much overhead in terms of data exchange or power loss.

In summary, MANETs are self-organizing and self-configuring networks that are inherently distributed. They have no single point of failure and are capable of re-routing around congested links. Their capability of sending packets of data over short

hops helps conserve power. Owing to their several attractive features, MANETs have become the preferred choice for autonomous mobile robot systems. The IEEE 802.11 standard in ad-hoc mode is the most prevalent MAC protocol for MANETs today [18].

## 2.2 Transmission power control in ad-hoc networks

The average MANET today works on a common-range transmission control [4]. That is, the transmission power of the transceiver is preset to a default value regardless of the node topology or network conditions. The distance over which the signal can be *heard* depends upon the value of transmission power. Consequently, a higher transmission power enables wireless nodes to communicate over longer distances. The optimal reception range of a wireless transceiver is not a fixed number. Transmission range plays a major role in determining the reception range. Effective transmission power control is a critical issue in the design and performance of inter-robot communication.

### 2.2.1 Trade-offs in transmission power control

From a network coverage point of view, it might seem that longer transmission range is better. This does not necessarily hold true. Admittedly, a longer transmission range reduces the number of hops that a packet needs to transverse in an ad-hoc network. But it also reduces network capacity and effectively increases access delay by increasing the number of nodes that locally compete on the shared channel. In contrast, short transmission range allows better frequency reuse and longer battery lifetime [16]. Also, more transmissions can occur in different areas of the network at

the same time, thereby improving the network throughput for a shorter transmission range [38]. Since the power consumed by the radio frequency (RF) power amplifier in a wireless module is directly proportional to the power of the transmitted signal, the node lifetime is greatly increased by lowering the energy required for transmission [18].

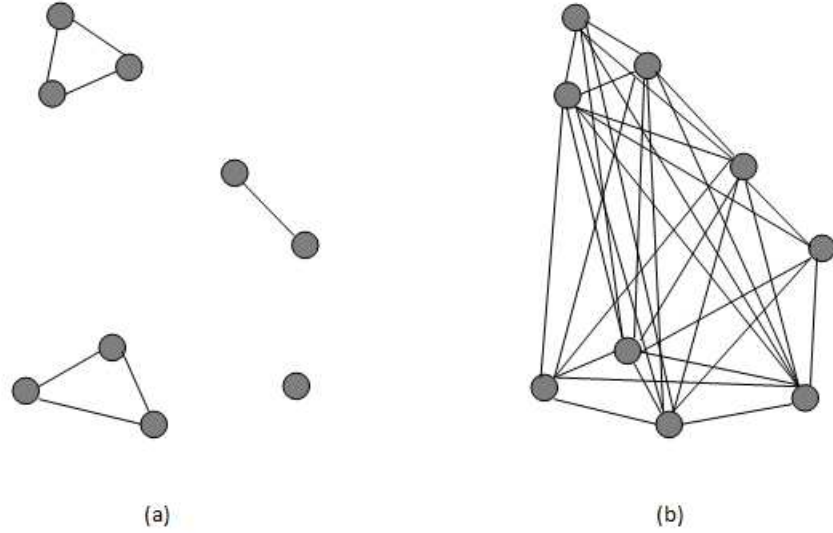


Figure 2.1: Network Connectivity (a) Low transmission range (b) High transmission range.

There is the caveat that, for a low transmission range, the chances of a network being partitioned increase. As illustrated in Fig. 2.1, there might be a situation where a node in one part of the network is unable to reach a destination node in another part of the network, irrespective of the number of hops. Such network division is detrimental to the ultimate application of the network.

From the above discussion, it follows that the key is to choose an optimal value of transmission power such that the network performance is improved in terms of energy-efficiency and throughput, while avoiding network partition. The next section

provides examples of the various approaches for transmission power control in the literature.

### **2.2.2 Transmission power control in the literature**

The topic of power control in MANETs has been extensively researched in recent times. The main objective of transmission power control has been to minimize energy expenditure for data delivery or to maximize network throughput by channel reuse mechanisms. Since the focus of this thesis is energy efficiency, only the literature on transmission power control for energy conservation will be discussed.

Network scientists primarily target two layers of the OSI model for energy-saving techniques- the Network Layer and the Data Link Layer [18]. At the Network Layer, Power-Aware Routing Protocols (PARPs) use energy-based metrics for route selection. Energy-aware path selection metrics include network connection longevity, node power variance, per-packet energy consumption, cost per packet and maximum node cost [39]. Proactive shortest path selection algorithms were the basis of the first generation PARPs. Nevertheless, such algorithms are more suited to stationary networks due to the control overhead incurred by proactive exchange of routing and power information with local neighbors.

Alternatively, on-demand routing techniques consume less power by avoiding such control data exchange overhead. One on-demand routing protocol that used power consumption to calculate link-weight is Power Aware Routing Optimization (PARO) [9]. Although PARO minimizes the overall transmission power consumed by the network, it fails to balance energy consumption among participating nodes.

Directional antennas are proposed in [31] to increase network lifetime and conserve energy. The scheme uses a metric based on “minimum energy consumed per packet” to build routes and then schedules node transmissions by maximum weight matching. Although this scheme is claimed to be more energy-efficient when compared to shortest path routing under omni-directional antennas, the single-beam directional antennas prove to be inadequate for time-sensitive applications as redirection of participating antennas cause large delays and increased energy consumption.

Though the PARP/PARO approaches result in energy conservation, their shortest path selection does not aim for optimality in route selection, leading to below-par network throughput. For instance, in Fig. 2.2, suppose node A wants to reach B. According to PARP, the packets meant for B are force-routed via the shortest next hop, node C, despite B being within the maximum transmission range of A. Also, the PARP approach does not take into account C’s neighbors that might wish to transmit. This leads to C’s neighbor nodes deferring their transmission until the channel is free again.

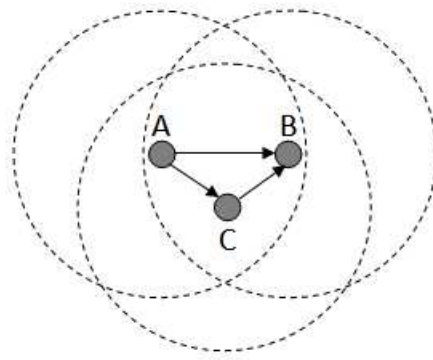


Figure 2.2: Limitations of the PARP/PARO approaches.

Although the transmission power is varied in the PARP/PARO approaches, their drawback is that, at the network layer level, it is not possible to change the channel reservation. The MAC layer is the obvious choice to enable a power controlled medium access solution. The literature shows that there are two ways in which such a solution might be achieved. The first is a topology control-based approach that aims to reduce the degree of the node while preserving connectivity. [42] proposes a distributed algorithm to increase the transmission power based on directional information till a neighbor node is found in every direction.

In [34], a distributed dual-phase position-based topology control algorithm is presented. A sparse enclosure graph is built based on broadcasted position information in the first phase. In the next phase, “optimal” links are determined from the value of a power consumption cost metric that is assigned to the links in the enclosure graph.

[38] et al undertake a graph theoretic approach to compute the *critical transmission range* for a wireless network, assuming that the locations of the nodes are known. This model, while allowing full network connectivity, is centralized, rendering it less practical for implementation in an ad-hoc network.

On the downside, topology control protocols rely on CSMA/CA for shared wireless channel reservation and access, significantly reducing throughput, delay and general network performance due to the infamous hidden terminal problem [18]. To deal with this lack of a channel reservation scheme, a second approach to MAC level power control is the more refined interference-awareness scheme [18]. Alternative approaches to transmission power control are clustering [19], joint clustering/TPC protocol [15], joint scheduling and power control [7].



### 2.2.3 Limitations of current approaches

In summary, contemporary transmission power control approaches utilize one of the following principles:

- Shortest path calculation with the weight of each link in the path being a function of a power-based metric [31] [15].
- Modification of existing MANET MAC protocols to promote lower transmission power levels in order to increase network capacity and network throughput [36][26].
- Algorithmically or mathematically determining an optimal transmission range for a given allowable power consumption [7] or connectivity [6, 1, 37, 25].

Despite their apparent advantages, there are some inherent drawbacks in the approaches described in the literature. Though there are protocols that claim to satisfy at least one of the most important network performance improvement metrics, namely, energy conservation or throughput enhancement or network connectivity, there are none that aim to achieve all three goals. Moreover, most of the approaches are based on specific routing protocols or are dependent on certain underlying mechanisms and fail to deliver as a standalone solution. Finally, to the author's knowledge, there is no transmission range control protocol that caters specifically to mobile robotic networks, whose unique characteristics merit investigation.

## 2.3 Cooperative Robotics Research at Auburn University

The work presented in this thesis is part of the Search And Rescue Algorithms (SARA) project at Auburn University. This section briefly describes the on-going project at the Cooperative Robotics Research Laboratory at Auburn University and its relevance to this thesis.

### 2.3.1 Laboratory environment

A collaborative team of six robots has been implemented in the laboratory. The functionality includes on-board processing, mobility and wireless capability. The laboratory experiment is carried out in a grid of dimensions 16 ft  $\times$  8 ft ( $\approx$  5 m  $\times$  2.5 m), with boundaries of cardboard walls. The 5 m long aisle is flanked by three rooms on either side with openings to serve as doorways. A simple room scenario was designed for this project. The robots are deployed in predetermined positions at one end of the room. That is, the initial pose of the robot is assumed to be known. Maps are exchanged thereafter to update each robot of the location of every other robot in the network. A stationary target cone is deployed at a random position when required. The robots perform a collaborative search of the environment for the stationary target. The robots use two 2800 mAh /7.2 V batteries for operation and are capable of motion at the rate of 0.5 inch per second ( $\approx$  0.0381 m/s).

### 2.3.2 Robot design

On the hardware side, the robots are designed with the following capabilities. They consist of an on-board Linux OpenEmbedded platform built on a Gumstix

Connex 400xm-bt motherboard based on the 400MHz Intel XScale PXA255 processor. The motherboard features a 64 MB SDRAM and 16 MB Flash Memory. Wireless connectivity is enabled by a wifistix expansion board that connects to the Connex motherboard via the 92-pin bus header. The wifistix FCC (with wifi antenna) uses standard 3.5V- 6V input. The on-board Marvell 88W8385 chipset provides IEEE 802.11a/b/g WLAN capability. (The 88W8385 enjoys embedded CPU and on-chip memory). Fig. 2.3 shows the equipment used in the laboratory.

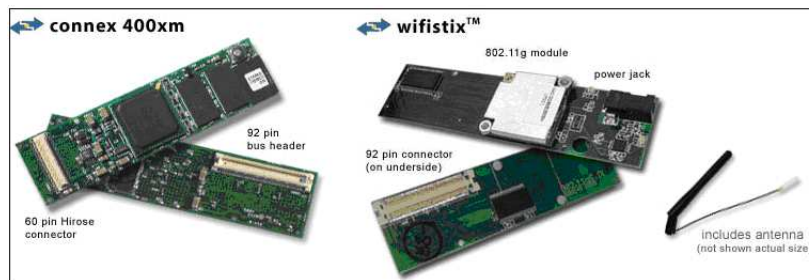


Figure 2.3: Connex 400xm-bt motherboard and wifistix used for communication

### 2.3.3 Cooperative operation

The objective of the robot team is to reconnoiter the area and locate the stationary target. Both exploration of the environment and location of the target require collaboration among the robots. The robots use SONAR to scan the area in order to identify and avoid obstacles (walls and fellow-robots). A search-and-rescue algorithm [32] was designed by the CRR team for this purpose. Servo motors control movement and coordination.

### 2.3.4 Communication network

The six gumstix robots are part of a WLAN (Wireless Local Area Network) with the fixed server acting as Base Station or Access Point. Due to processing power constraints, the robots are currently designed to communicate with only the BS and not peer-to-peer. Collaborative robotics calls for regular communication and exchange of information between the robots. Since an ad-hoc design is more suitable for real-world collaborative search-and-rescue operation, an ad-hoc peer-to-peer network is used in the experimental simulations. When modeling a robotic sensor network, it is important to note the environmental aspects in terms of communication features required. Key characteristics of the above scenario can be summarized as follows:

- Limited number of robotic nodes.
- The nodes need to be fully mobile.
- Since the robots are equipped with wi-fi modules capable of operating IEEE 802.11a/b/g, the best technology should be chosen depending on energy constraints and other properties of the network.

For the sake of generalization, a random deployment is considered in this work. Keeping in mind that the eventual implementation would be in an outdoor environment, a more general rectangular area is considered for our experimental purposes.

## CHAPTER 3

### THE TRANSMISSION POWER CONTROL PROTOCOL

#### 3.1 Objective

According to [2], the fundamental issues that need to be addressed in inter-robot communication are:

- Is communication necessary?
- Over what range do we need to communicate?
- What information do we need to convey?
- Is the communication guaranteed?

Of these, the second issue is the most pertinent to this thesis. Thus, a key issue in providing cost effective communication for a mobile robotic network is to find a ‘sufficient’ value of transmission power for each robot to be able to communicate efficiently with every other robot in the network.

We have seen in earlier sections that varying the transmission power has two-pronged effects. Increasing the transmission power usually results in lesser number of hops between the sender and the receiver. But this increased connectivity comes at the price of causing more contention for an already-shared medium and increased energy consumption [18] [28]. Lowering the transmission power has the opposite

effect of reducing the interference seen by other potential transmitters and lower power consumption in general, but results in a higher number of hops from source to destination. Consequently, the usual solution is to find an acceptable tradeoff between connectivity and energy consumption. Connectivity, however, is a critical issue in cooperative robotics, and cannot be taken for granted.

Hence, the goal is to provide a simple method of variable transmission power control to conserve energy without sacrificing connectivity. Moreover, the algorithm put forth in this thesis is protocol-independent, rendering interoperability and backward-compatibility a non-issue. Most importantly, the proposed transmission power control protocol exploits two distinguishing characteristics of collaborative mobile robotic networks:

**Cooperative communication** In a collaborative robotic network, the robots receive frequent updates of each other's location and position information. This helps the robots build a global map of the environment based on the individual local maps. In the context of this thesis, cooperative communication between robots will be defined as data exchange between multiple robots that facilitates better performance of a task than when performed by an individual robot.

**Predictable mobility** Collaborative robots are usually deployed on mission-oriented tasks. This implies that the mobility is planned to a certain extent and is fairly predictable. The inherent cooperative communication also helps in estimating the future position of any single robot. Contrastingly, in common MANETs, mobility models based on statistical or random patterns are used for evaluating protocols.

To the author’s knowledge, no communication protocol aimed at energy conservation via transmission power control takes these unique features of a collaborative mobile robot network into consideration.

Lastly, mobile robot applications have limited on-board computational capacity, combined with a severe restriction of power resources. Thus, any communication model designed for mobile robotic networks need to be simple and easy to implement without hogging memory, power or computing resources.

### **3.2 Transmission Power Control Protocol (TPCP)**

In this section, the proposed algorithm is explained and the simulation results are presented. The mobile robots are referred to as nodes frequently in the rest of the discussion. The basic concept behind the *Transmission Power Control Protocol* (TPCP) is presented first, followed by a more detailed explanation of the proposed algorithm.

#### **3.2.1 Basic concept**

The proposed algorithm is completely distributed, enabling each robot to vary its transmission power autonomously. There is no infrastructure or centralized point of control involved, eliminating the problem of a single point of failure.

Initially, for any topology of ad-hoc networks, each node transmits at a default power level to achieve the maximum transmission range. This range is set to ensure maximum connectivity of nodes. Fixing the transmission to the maximum possible value, however, may not be the most energy-efficient way to communicate in a collaborative robot network.

Consider Fig. 3.1, where we have assumed a simple linear topology of four immobile nodes. In this scenario, B lies in the transmission radius of A. Hence, B is a *neighbor* of A. Similarly, since A and C are within the transmission range of B, they are considered B's neighbors. The *neighbor set* of a node is defined as the set of all single-hop neighbors of a node.

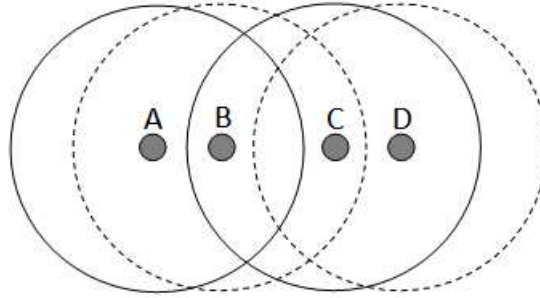


Figure 3.1: Linear topology of four nodes with fixed transmission range.

The transmission power level of all four nodes in Fig. 3.1 is set to the default value, enabling them to cover the same maximum transmission radii. It is obvious that, strictly speaking, if A reduces its transmission power to, say half its original value, it can still communicate effectively with its neighbor, B. By a similar logic, D can communicate with C with a much smaller fraction of power. Such a scenario is shown in Fig. 3.2, where A and D have reduced their transmission ranges suitably. It is important to note that in Fig. 3.2, both A and D still boast the same connectivity and neighbor set as before. More significantly, the two nodes now use much lesser energy than before, owing to the lower power levels required for the new contracted transmission ranges.

It can be argued that the linear topology with stationary nodes used above is too simplistic to be applicable to real-world scenarios. Therefore, in the following discussion, movement of nodes is considered. Fig. 3.3 depicts a 3-node topology in



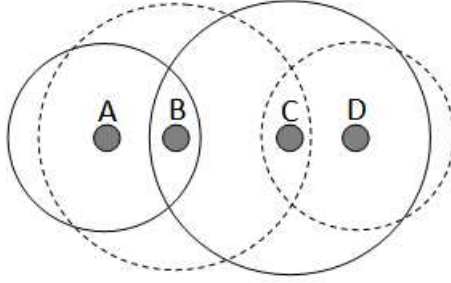


Figure 3.2: Linear topology of four nodes with adjusted transmission range.

which C is mobile. Node C moves away from A with a specified velocity along the indicated path. Suppose that A is aware of C's velocity and direction of motion and that A updates its transmission range every  $\Delta t$  seconds. Node A *predicts* the location of C every  $\Delta t$  seconds as shown in Fig. 3.3.

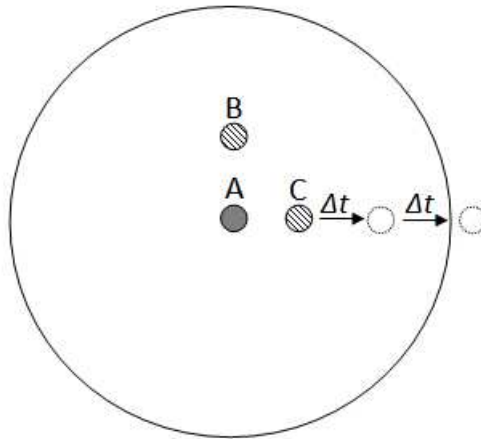


Figure 3.3: Position of C every  $\Delta t$  seconds.

Node A's initial transmission range is shown in Fig. 3.3. When A wants to update its transmission range at time  $t$ , it calculates the positions of all its neighbors at  $t + \Delta t$  seconds. Node A then modifies its transmission radius to encompass its farthest neighbor after  $\Delta t$  seconds. Fig. 3.4 illustrates this mechanism.

Successive snapshots of the network topology and the updated transmission range of A at  $t$ ,  $t + \Delta t$  and  $t + 2\Delta t$  are shown in Fig. 3.4 (a), (b) and (c) respectively. In

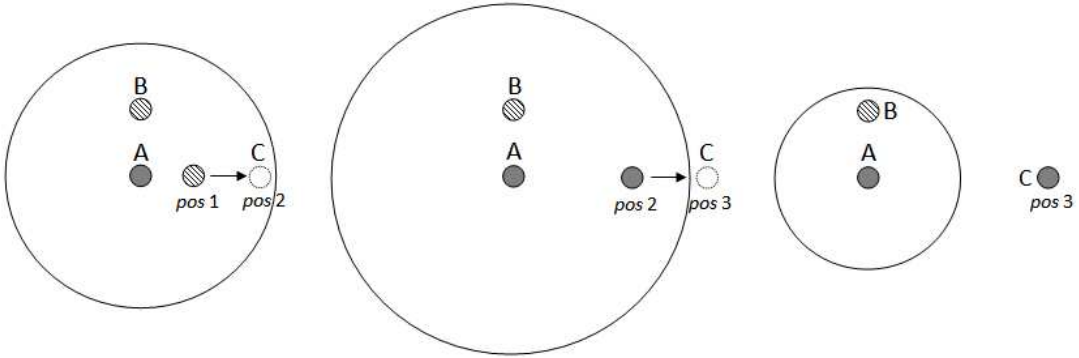


Figure 3.4: Snapshot of Node A's transmission range every  $\Delta t$  seconds.

(a), A has proactively lowered its transmission range just enough to cover *position 2* of node C. This is because, the next transmission range update will occur only after  $\Delta t$  seconds. After  $\Delta t$  seconds, when node A wants to update its transmission range again, it predicts that C will move *out of its transmission range* in the next  $\Delta t$  seconds. So, A expands its transmission radius to the maximum possible value to accommodate C's movement till C's departure from A's coverage area, as shown in (b). After C has moved out, A contracts the transmission radius to fit only its now-farthest neighbor, node B, as shown in (c).

This simple strategy to conserve transmission power without losing connectivity forms the nucleus of the proposed algorithm. The details of the *Transmission Power Control Protocol* (TPCP) for Collaborative Robotic Networks are put forth in the next section.

### 3.2.2 Description of the proposed algorithm

Before the Algorithm is described it is important to understand the different *Phases* and the assumptions made in this protocol.

**Initialization Phase** To begin with, all the robotic nodes are deployed either randomly or strategically in the target area. No node has prior information about its neighbors. Each node broadcasts its initialization data on the network to advertize its ready-state.

**Reconnaissance Phase** Each robot scans its surroundings to build a *local map* depicting its immediate environment. This map, consisting of the node's current position data and perceived environment information, is then broadcast to the group.

**Map-building Phase** The node then processes the received information to build a *global map*, incorporating the relative positions of the other nodes in the network. This procedure serves to identify a specific node's *neighbor set*. These maps are exchanged among all the nodes periodically. At the end of the *Map-building Phase* all the nodes would be receiving the maps from their neighbors periodically. This is called *Steady State of the Network*. The proposed algorithm is implemented in the *Steady State of the Network*. The following steps illustrate the algorithm in detail:

**Step 1** In the *Map-building Phase*, the initial transmission power is set according to the transmission range specifications of 802.11g for a data rate of 54 Mbps. Suppose that the default transmission range of 802.11g is  $T_r$  and the power corresponding to  $T_r$  is  $P_{T_r}$ . The transmission range is updated every  $t_U$  seconds.

**Step 2** Each node deduces the current coordinates of its neighbors from the most recently received map. It then calculates the distance between itself and its neighbors using the location information from the map. Let  $N$  represent the set of nodes,  $NN_i$

represent the set of neighbors of node  $N_i$  and  $d_{ij}$  represent the distance between node  $N_i$  and node  $N_j$ . Distance  $d_{ij}$  is calculated as

$$d_{ij} = \sqrt{(x_i - x_j)^2 + (y_i - y_j)^2}$$

where  $(x_i, y_i)$  and  $(x_j, y_j)$  are the coordinates of the sender and receiver node respectively.

**Step 3** Obtain the position information of the neighbors from the exchanged map data. Predict the velocity and direction of motion and calculate the relative velocity of the neighbors.

**Step 4** Recalculate the Effective Distances,  $d_E$  of each neighbor from the source node. Effective distance,  $d_E$  is sum of the current distance,  $d$ , and the distance a node's neighbor would travel in the next  $t_U$  seconds. The distance travelled in  $t_U$  seconds is represented as  $d_U$ .

$$d_{E_{ij}} = d_{ij} + d_{U_{ij}}$$

where  $d_{E_{ij}}$  represents the effective distance between  $N_i$  and  $N_j$ .

**Step 5** Choose the maximum distance  $d_{E_{ij}}$  for each node and calculate the corresponding transmission range. Then calculate the transmission power corresponding to that transmission range.

**Step 6** Change the transmission power to the calculated power and repeat the process after  $t_U$  seconds. If a node does not have any neighbors, then set the transmission power to the default transmission power,  $P_{T_r}$  corresponding to the range  $T_r$ .

A flowchart illustrating TPCP is given below:

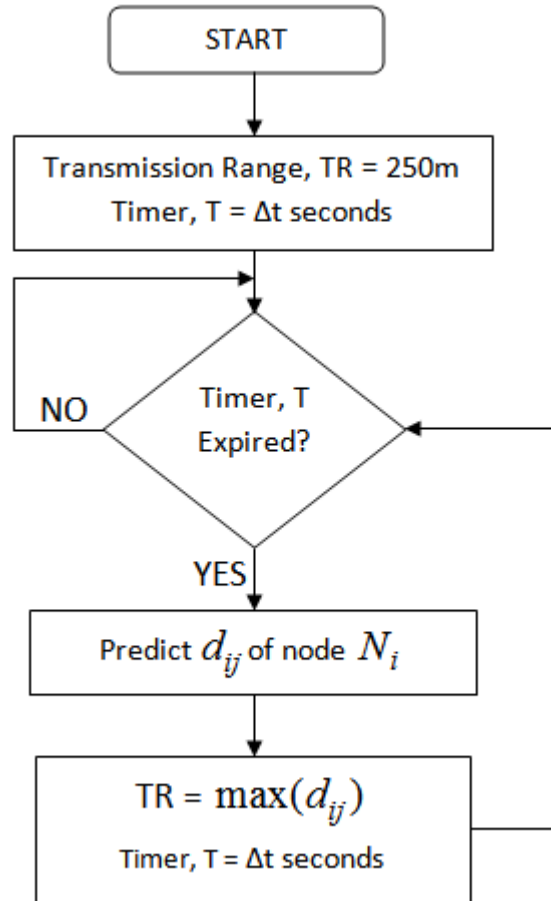


Figure 3.5: Flowchart of TPCP.

## CHAPTER 4

### EXPERIMENTAL RESULTS

In this chapter, the Transmission Power Control Protocol (TPCP) is compared with the conventional method of fixed transmission range for all the nodes and the energy efficiency of the proposed algorithm is studied.

#### 4.1 Simulation Setup

The performance evaluation of the TPCP algorithm is made via simulations using MATLAB 7.0. In the initial set of experiments, the nodes (robots) are considered to be stationary. The nodes are randomly deployed in a 1000 m  $\times$  1000 m area. The number of nodes is varied from 1 to 50 in the simulations. Each point on the graphs is an average of 100 experiments in order to average out the randomness. In the second set of experiments mobile nodes are considered. To account for the mobility of the robots, the Random Waypoint Mobility Model is used. The Random Waypoint Mobility Model is written in MATLAB, the code of which is available in Appendix A. The velocity of nodes is fixed to be 5 m/s in the experiments. The option to use variable velocity for each node is also embedded in the code for the sake of completeness. The transmission power is changed every one second. This is a variable which can be adjusted according to the situation, the effect of which is analyzed later in this section. The default transmission range is considered to be 250 m as it is in the case of IEEE 802.11 nodes. The power corresponding to the

Table 4.1: Simulation Parameters

Parameters	Value
Area	1000 m $\times$ 1000 m
Number of Nodes	Varies from 1 to 50
Default Transmission Range	250 m
Mobility Model	Random Way Point
Velocity	Fixed speed of 5 m/s
Pause time	0 s
Transmission Range Update Interval ( $\Delta t$ )	1 s

default transmission range is 281.83 mW. The power required by TPCP is termed as Critical Transmission Power (CTP). The effect of external factors has been neglected in calculating the CTP for a given transmission range so that the desired relation between transmission power and the value under consideration is highlighted. The parameters used in the simulation are summarized in Table 4.1.

## 4.2 Results and Analysis

Fig. 4.1 shows the aggregate energy spent in a stationary network as the number of nodes is increased. *Aggregate energy* is defined as the total energy spent by all nodes if every node broadcasts one 1000 byte packet with its allocated transmission power. From the graph, it is clear that the aggregate energy consumed in the TPCP case is less than when the nodes are broadcasting using the conventional fixed transmission power approach. As expected, the energy consumed by the fixed transmission range approach increases linearly with node density. On the other hand, the energy savings by TPCP is small initially, but increases substantially for higher node densities. In

fact, as the number of nodes in the network increases, there is an energy savings of up to 20%.

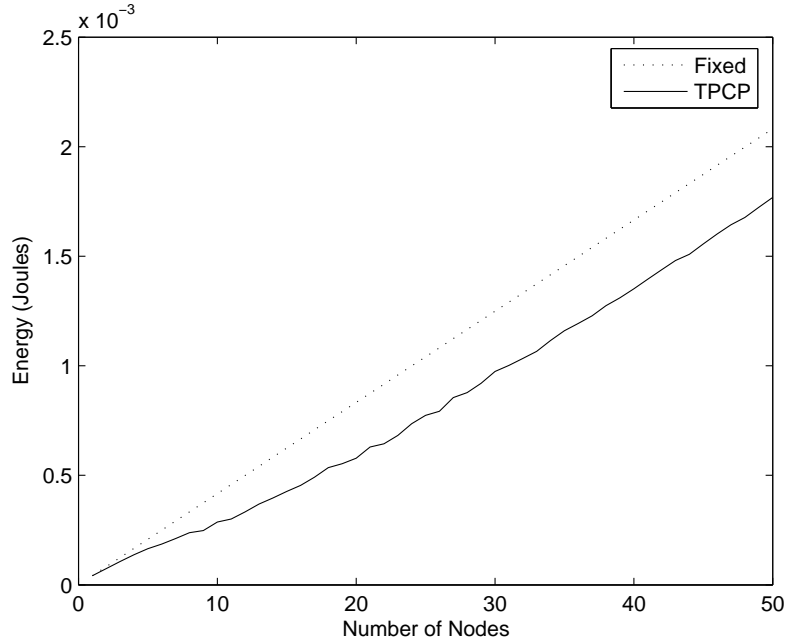


Figure 4.1: Variation of the aggregate energy in a stationary network.

In the next set of experiments, node movement is considered. For a set of 20 nodes moving with a constant node velocity of 5 m/s according to the Random Waypoint Mobility Model, Fig. 4.2 shows the time evolution of the energy consumed in the simulations. The straight line at about 2.08 mJ is the constant energy consumed by the fixed transmission power model. It is interesting to note that the chaotic pattern of energy consumption in TPCP caps at a maximum of 1.90 mJ in this experiment. Although it is bounded, the TPCP energy consumption seems to have chaos characteristics; so time evolution does not provide much information about the process. As the nodes are moving in and out of the transmission ranges of other nodes



in the network in a random fashion, it is natural that, according to TPCP, the CTP changes with the minimum coverage area required to maintain connectivity.

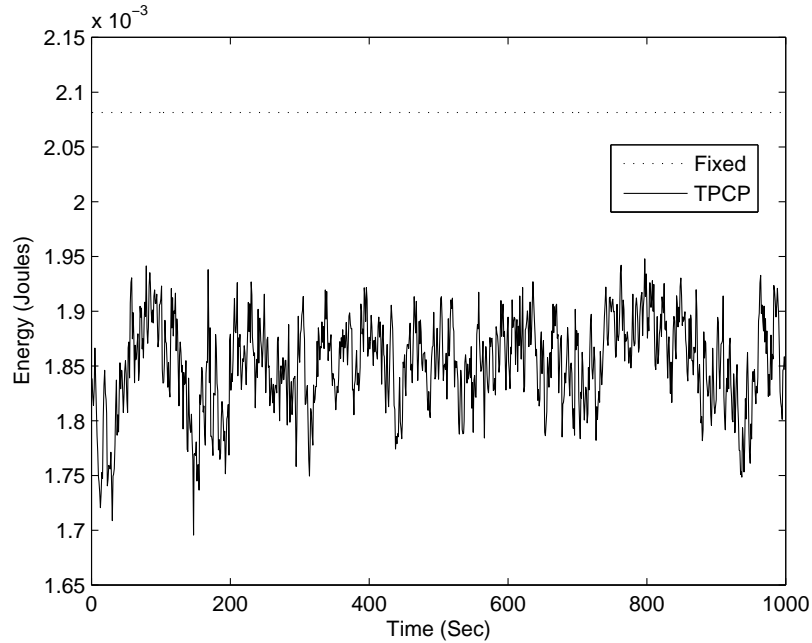


Figure 4.2: Variation of aggregate network energy with time in a mobile network with fixed transmission range and TPCP approaches.

The variation of energy consumption in TPCP with the number of nodes in a random mobile network is shown in Fig. 4.3. The trend is observed to be similar to that of a stationary network. This is because the network topology at any given instant of time in a stop-and-go robotic network is essentially a stationary snapshot of the nodes between motion. Thus, the energy consumption behavior with varying number of nodes at any given instant of time is similar in stationary and mobile networks. It is observed that the energy consumption of the TPCP approach is lesser than the fixed transmission range approach.

A comparison of TPCP performance using two most popular open-space radio propagation models is shown in Fig. 4.4. The graph shows the variation of aggregate

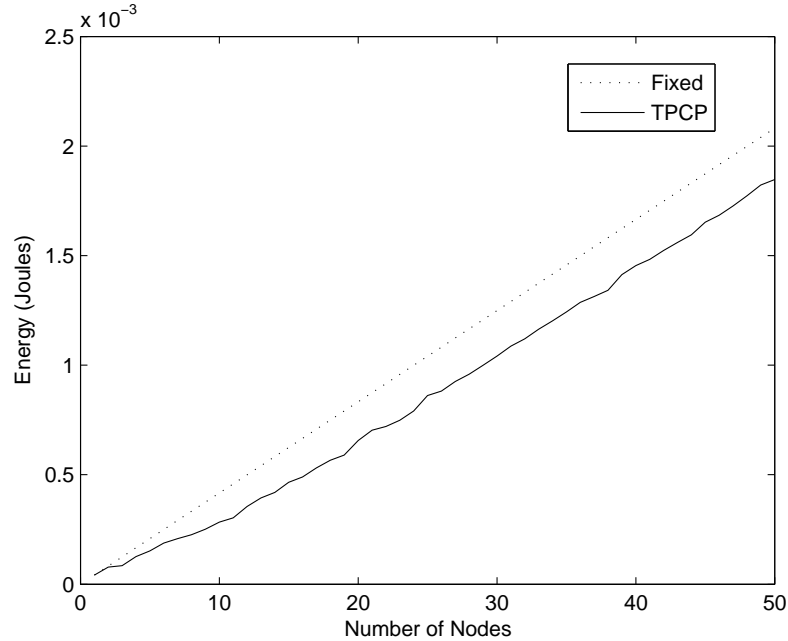


Figure 4.3: Variation of the aggregate energy in a mobile network.

energy in a mobile network for the conventional fixed transmission approach and two different radio propagation models. The results indicate that TPCP has better energy savings with the two-ray ground propagation model ( $P_r \propto P_t/d^4$ ) than the free-space propagation model ( $P_r \propto P_t/d^2$ ). This can be explained as follows. Suppose that the transmission range is halved using TPCP. In this case, for a required level of received signal power with the two-ray and free-space models, the transmission power need only be one-sixteenth and one-fourth, respectively. Hence, TPCP gives different energy savings depending on the radio propagation model used.

Fig. 4.5 shows a histogram of the TPCP transmission range with 50 nodes randomly deployed in a  $1000 \text{ m} \times 1000 \text{ m}$  area. The histogram indicates that several nodes could reduce their transmission ranges below the default transmission range of 250 m without compromising network connectivity.

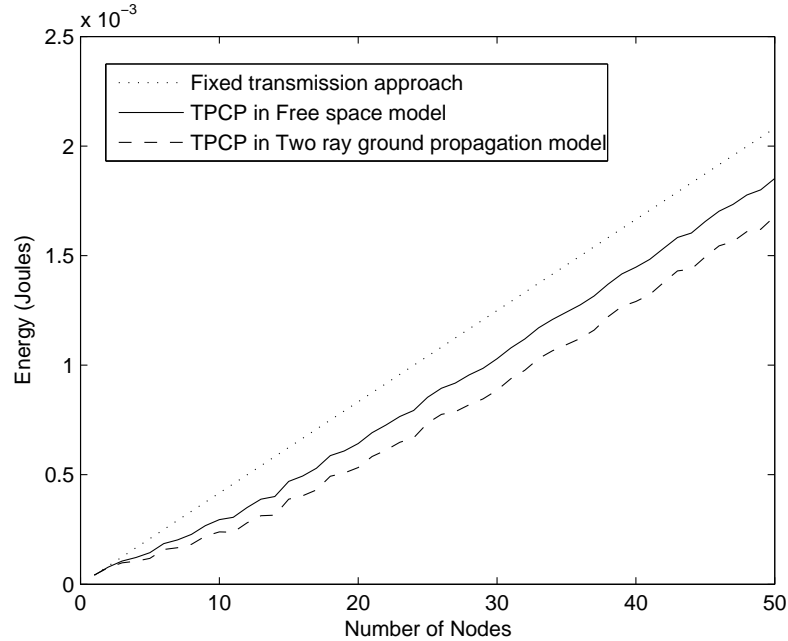


Figure 4.4: Variation of the aggregate energy in a mobile network with different radio propagation models.

The critical transmission radius in the simulation of Fig. 4.5 ranges between 150 m and 250 m. This is because the simulation is of a stationary network of nodes deployed in a uniformly random fashion. As a result, the nodes are spread out over an area of  $1000 \text{ m}^2$ , confining the critical transmission radius to a bounded range determined by the simulation. This prevents TPCP from exploring much lower values.

In a mobile network, the continuous movement of nodes ensures that neighboring nodes undergo extremes of proximity with time. That is, there is a possibility that nodes move much closer or much farther than the default transmission radius. This enables the TPCP mechanism to dynamically change the CTP to much lower values. For example, in Fig. 4.6, critical transmission radii in the order of tens of meters are utilized. Fig. 4.6 is a 1000 second simulation run for 20 mobile nodes in which the

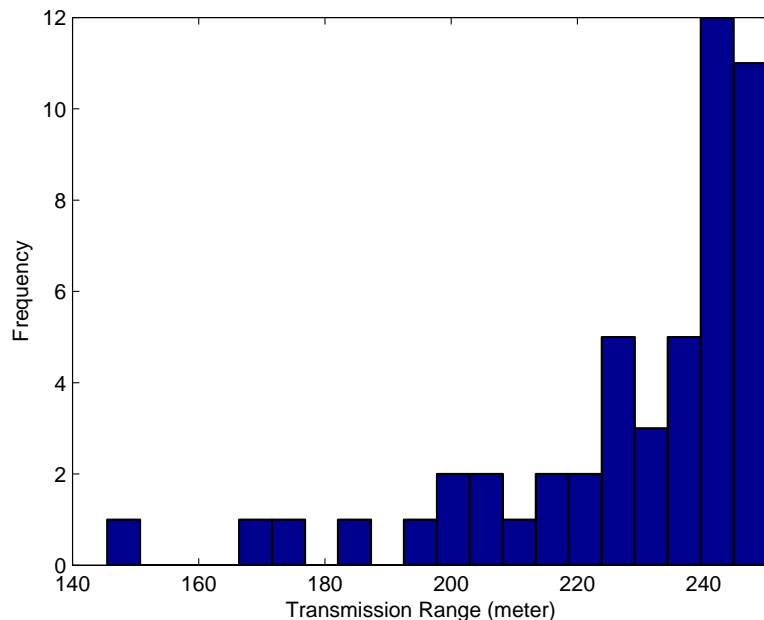


Figure 4.5: Histogram of critical transmission ranges in a 50-node stationary network.

critical transmission range was updated every 1 second resulting in the corresponding frequency distribution.

The frequency histogram of discrete transmission range levels for a simulation of 20 mobile nodes for 1000 seconds is shown in Fig. 4.7. The histogram indicates that, on an average, 25% of the neighbor set existed between 150 m and 200 m. In fact, 30% of all neighboring nodes required a transmission range lesser than 150 m. This implies that for all those nodes utilizing 100 m more than strictly necessary, the energy consumed would be much higher than that required by using TPCP. In addition, those nodes transmitting over a longer distance would be potentially increasing the interference seen by other nodes in the network.

The simulations of Fig. 4.6 and 4.7 assume a continuum of transmission ranges. Generally, varying transmission power levels over a continuous range is not practical.

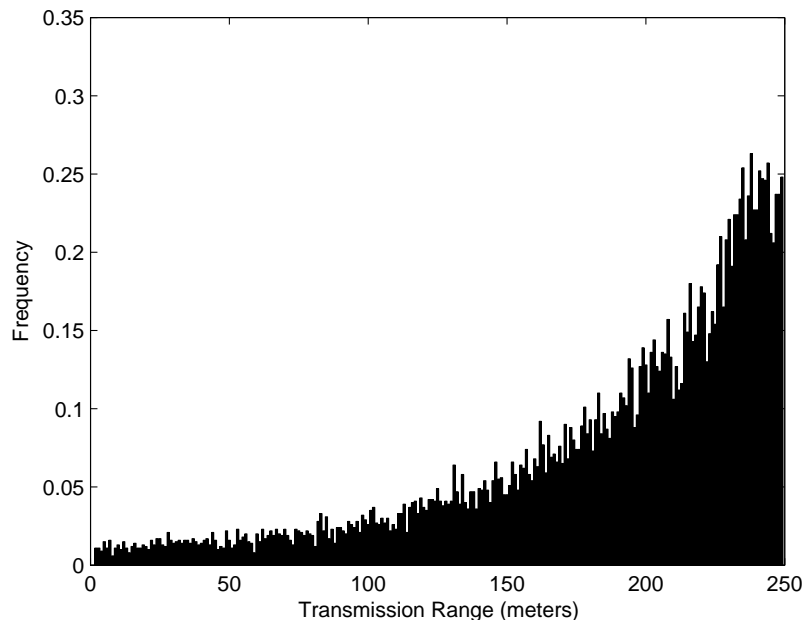


Figure 4.6: Histogram of critical transmission ranges in a 20-node mobile network.

In a real-world environment, it would be more practical to consider discrete transmission power levels. This led to another set of experiments where discrete levels of CTP are chosen. Here, five equidistant discrete levels of CTP were chosen between 0 m and 250 m and the node density was varied between 0 and 50. A graph was plotted between the number of mobile nodes and aggregate energy consumption. It is noted that though this graph is similar in trend to the one obtained for continuous variation of CTP Fig. 4.2, the energy consumption using TPCP is slightly more than it was previously.

The discretization of CTP levels in TPCP causes a slight decrease in power savings. Consider Fig. 4.8 where the node A has five discrete CTP levels of 50, 100, 150, 200 and 250 meters respectively. Suppose node B has moved into the transmission region of node A. Here, though B is located at a distance of only 151 m from A, A

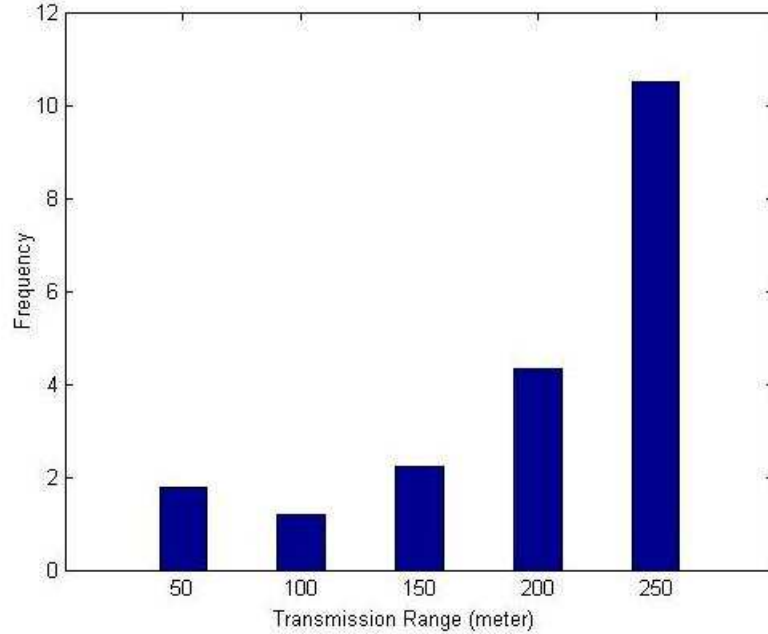


Figure 4.7: Histogram of discrete critical transmission ranges in a 20-node mobile network.

would still have to increase its transmission radius to 200 m because the discrete CTP level of 150 m would not be sufficient for communication.

In order to optimize TPCP performance, two different degrees of discretization were considered. In Fig. 4.10, the node density is plotted against energy consumption with five and ten different levels of CTP. It is observed that the energy consumption decreases for a higher degree of discretization. It is necessary to find an optimal value of discretization levels. Discretization of critical power transmission levels is also dependent on the hardware used and the mobility of the nodes in the network. Hence, the degree of discretization should be chosen such that the power savings has a significant advantage for the hardware and network under consideration. Also, in Fig. 4.10, the CTP was updated every  $\Delta t = 1$  s. Frequent variation of CTP is not

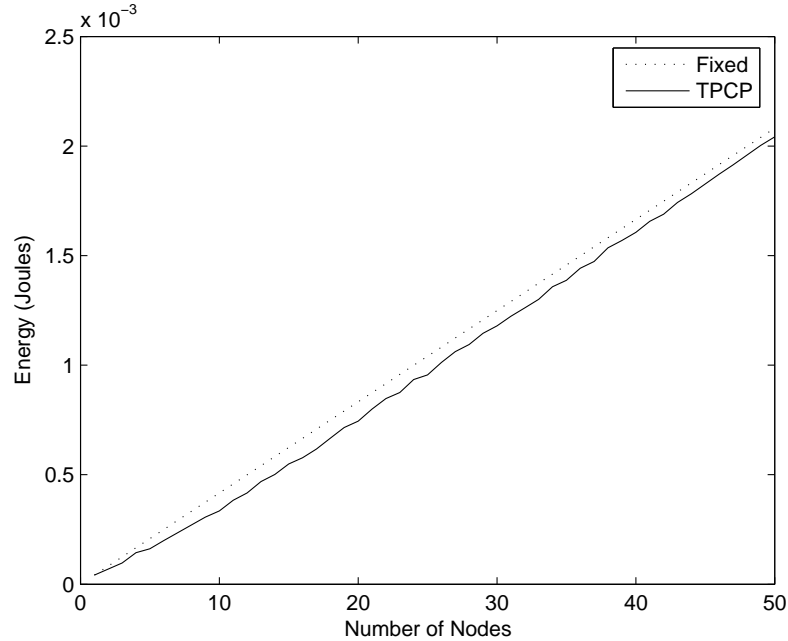


Figure 4.8: Variation of aggregate network energy with node density in a mobile network with fixed transmission range and five-level discrete critical transmission range approaches.

a practical option as it is bound to drain more energy than it saves. Care should be taken while choosing the value of  $\Delta t$ .

The viability of a communication protocol is judged by its applicability in a real-world scenario. The simulations performed thus far were for the transmission of a single 1 kbyte packet. To model the utility of the Transmission Power Control Protocol proposed in this thesis, the robot built at the Cooperative Robotics Research Laboratory at Auburn University was considered.

In Fig. 4.11, the number of packets sent over the network is plotted against the energy consumed. As the number of packets of data sent over the network increases, it is observed that the energy consumed drops significantly; suggesting that power savings with TPCP is substantial when considered for a longer period of communication. Each robot in the cooperative robot network has one 2800 mAh battery capped at

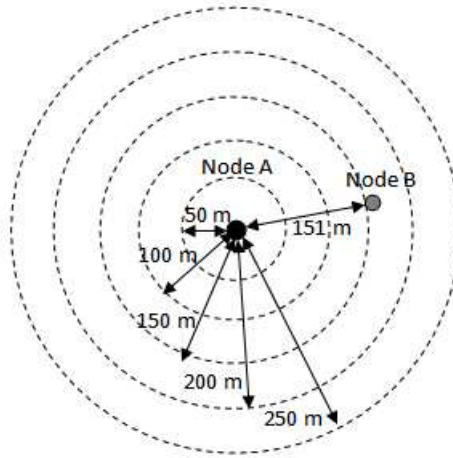


Figure 4.9: Five-level discrete transmission ranges.

5 V dedicated to SONAR and on-board computer. The wireless network transceiver can typically use 15 – 30% of the power of a mobile computer [33]. Suppose 20% of the total battery power were to be used solely for communication purposes. Also, assume data is transmitted continuously at a traffic rate of 54 Mbps. This implies that 6750 1 kB packets can be sent per second.

Total energy available for communication is  $(560 \times 10^{-3} \times 5 \times 3600)$  J = 10080 J.

From the graph, it is observed that the conventional fixed transmission power approach can support transmission of  $12.1 \times 10^6$  data packets with this energy.

On the other hand, using the TPCP approach, a transmission of  $15.6 \times 10^6$  data packets can be sustained by the same battery power.

In other words, the TPCP approach can effectively support transmission of  $3.5 \times 10^6$  data packets more than the conventional approach. This implies, for the assumed traffic rate, network lifetime is increased by 28.9%.

The assumed traffic rate of 54 Mbps is much higher than practical values. Thus, it is



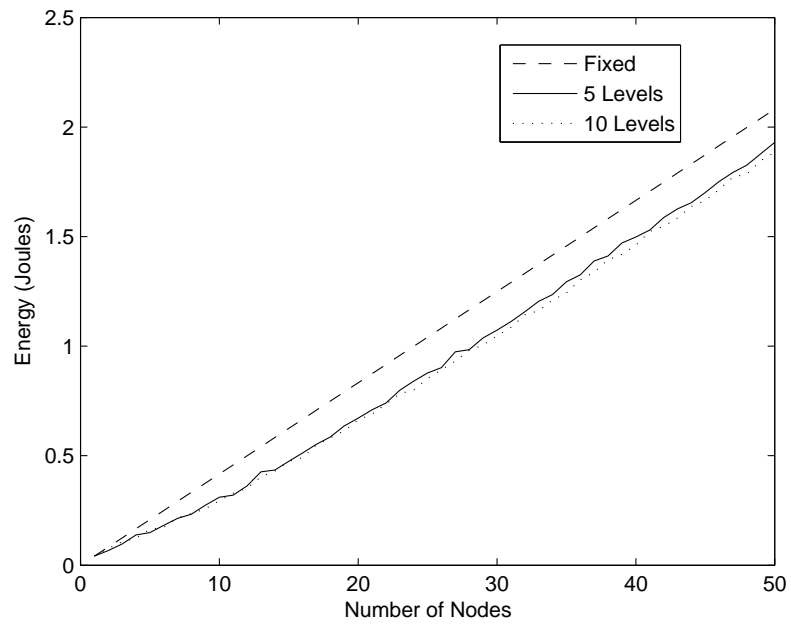


Figure 4.10: Variation of aggregate network energy with node density in a mobile network for different levels of discretization.

expected that the TPCP will yield even better results in real-world scenarios.

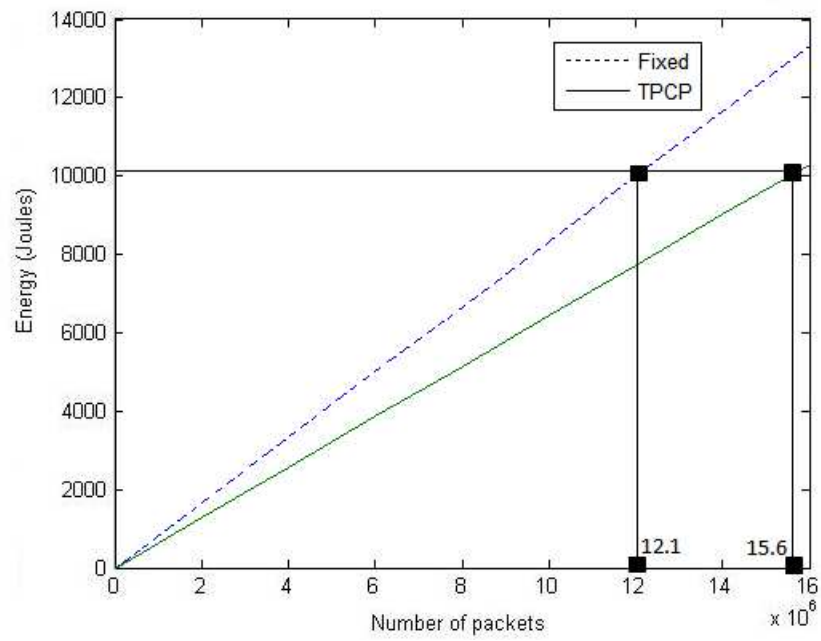


Figure 4.11: Variation of aggregate energy spent with number of transmitted packets in a mobile network.

## CHAPTER 5

### CONCLUSIONS

A simple yet efficient method to compute and control the energy used for communication in a cooperative robotic network has been presented. The Transmission Power Control Protocol, referred to as TPCP, was based on the variation of the transmission power of the autonomous nodes in a cooperative robot network. It was shown that the algorithm supports mobility, preserves connectivity and reduces interference seen by other nodes in the network.

The transmission range of the nodes was varied according to the position of their neighbor nodes in the network, making it essentially a proactive protocol. When a node has a set of neighbors, the transmission range takes the value of its farthest neighbor, but no more. If the node has no neighbors, the transmission range is set to the maximum possible value. The transmission power is regularly adjusted to meet the above transmission range requirement resulting in frequent low power transmissions. This algorithm reduces the energy usage of the nodes while ensuring the same connectivity as the conventional approach.

The TPCP has been simulated in MATLAB using the Random Waypoint Mobility Model to model the node movements. The results suggest that there is above 20% energy conservation when compared to the conventional approach of fixed transmission ranges.

## 5.1 Contribution to the Field of Communication in Cooperative Robotics

This thesis has presented, to the author's knowledge, a novel energy-efficient protocol for transmission power control in cooperative robot networks implemented using MATLAB 7.0. There have been few instances in the literature where energy-aware cooperative robot communication is treated from the standpoint of transmission range variation.

This algorithm is different from previous algorithms for transmission power control in that it achieves energy efficiency without compromising network connectivity or burdening the on-board processor of a mobile robot with complex computations.

## 5.2 Suggestions for Future Work

- Study the effect of different mobility models on the Transmission Power Control Protocol (TPCP).
- Implement TPCP on the CRR laboratory's mobile robots.

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## APPENDICES

## APPENDIX A

### MATLAB SOURCE CODE

The MATLAB programs used to simulate the Transmission Power Control Protocol (TPCP) are presented here.

#### A.1 Immobile Nodes

This is the code to implement a random scenario of immobile nodes and vary their transmission range according to the Transmission Power Control Protocol (TPCP) and plot the graph of actual energy of the network versus the optimal energy of the network. It also plots the histogram of the critical transmission ranges.

```
1 clear all;
2 for Number_of_Nodes = 1:50;
3 % Number_of_Nodes = 100;
4 % Define the area
5 x_max = 1000;
6 y_max = 1000;
7
8 % Assign random positions for each node
9 node_x_axis = ceil(rand(1,Number_of_Nodes)*x_max);
10 node_y_axis = ceil(rand(1,Number_of_Nodes)*y_max);
11
12 %Initialize the neighbors of all nodes to Zero
13 node_neighbors = zeros(Number_of_Nodes,Number_of_Nodes,2);
14
15 % Find the neighbors of each node
16 for i = 1:Number_of_Nodes
17     for j = 1:Number_of_Nodes
18         distance = sqrt((node_x_axis(i)-node_x_axis(j))^2 ...
19             + (node_y_axis(i)-node_y_axis(j))^2);
20
21         if(distance<250)
22             node_neighbors(i,j,1) = 1;
23             node_neighbors(i,j,2) = distance;
24         end
25     end
26 end
27
```

```

28 % scatter(node_x_axis,node_y_axis);
29 node_transmission_range = zeros(1,Number_of_Nodes);
30
31 % Find the minimum transmission ranges
32 node_transmission_range = max(node_neighbors(:, :, 2), [], 2);
33
34 % Set the transmission range of neighborless nodes to zero
35 node_transmission_range((node_transmission_range==0)) = 250;
36 % figure(1);
37 % hist(node_transmission_range, 50);
38
39 p = (281*10^-3)*((1000*8)/(54*10^6));
40
41 actual_node_energy = zeros(Number_of_Nodes,1)+p;
42 optimal_node_energy = ((node_transmission_range.^2))*p/(250^2);
43 % optimal_node_energy = node_transmission_range*(281*10^-3)*
44 % ((1000*8)/(54*10^6))/250;
45
46 actual_total_energy(Number_of_Nodes) = sum(actual_node_energy);
47 optimal_total_energy(Number_of_Nodes) = sum(optimal_node_energy);
48
49 end
50 Number_of_Nodes = 1:50;
51 figure(1);
52 plot(Number_of_Nodes, actual_total_energy,Number_of_Nodes,...
53      optimal_total_energy);
54 % a = hist(node_transmission_range, 20);
55 % hist(node_transmission_range, 20)

```

## A.2 Mobile Nodes

This is the code to implement a random scenario of mobile nodes using Random Way Point Mobility model. The transmission range of the nodes are varied according to the Transmission Power Control Protocol (TPCP) and the graph of actual energy of the network versus the optimal energy of the network is plotted. This program uses the user defined functions, *energy\_function.m* and *energy\_function\_discretized.m* to calculate the optimal energy of the network in continuous as well as discretized scenarios. These functions are presented later in this section.

```

1 % Random Way Point Model
2 clear all;
3
4 for temp =1:50
5
6     temp
7 % Specify the Dimensions of the Grid
8 x_max = 1000;

```

```

9  y_max = 1000;
10
11 %Specify the Number of Nodes
12 Number_of.Nodes = temp;
13
14 %Specify the maximum speed
15 Speed_Max = 10;
16
17 n = Number_of.Nodes;
18 final_x = ceil(rand(1,n)*x_max);
19 final_y = ceil(rand(1,n)*y_max);
20
21 x_axis_next = final_x;
22 y_axis_next = final_y;
23 % h = plot(x_axis_next,y_axis_next, '.');
24 % axis([0 x_max 0 y_max])
25 % axis square
26 % grid off
27 % set(h, 'EraseMode', 'xor', 'MarkerSize', 5, 'Marker', 'o')
28 status = zeros(1,n);
29 step = 1;
30 k = 1;
31 for i = 0:step:999
32     %Delay
33     %for j = 1:1:10000 end
34     for j = 1:n
35         if (status(j) < step)
36             x_axis_old(j) = final_x(j);
37             y_axis_old(j) = final_y(j);
38             final_x(j) = ceil(rand(1,1)*x_max);
39             final_y(j) = ceil(rand(1,1)*y_max);
40             distance(j) = sqrt((final_x(j)-x_axis_old(j))^2 ...
41                               + (final_y(j)-y_axis_old(j))^2);
42             % speed(j) = ceil(rand(1,1)*Speed_Max); % For Random velocity
43             speed(j) = 5; % For Random velocity
44             status(j) = (distance(j)/speed(j));
45             slope(j) = (final_y(j)-y_axis_old(j))/...
46                       (final_x(j)-x_axis_old(j));
47             Δ_t(j) = 0;
48         end
49     end
50     Δ_d = Δ_t.*speed;
51     temp_x = x_axis_next;
52     temp_y = y_axis_next;
53     x_axis_next = x_axis_old + (Δ_d).*sqrt(1./(1+slope.^2));
54     y_axis_next = slope.*(x_axis_next - x_axis_old) + y_axis_old;
55
56     for j = 1:n
57         if ( ((x_axis_next(j) > x_axis_old(j)) && ...
58              (x_axis_next(j) > final_x(j))) || ...
59              ((x_axis_next(j) < x_axis_old(j)) && ...

```

```

60         (x_axis_next(j) < final_x(j)) || ...
61     ((y_axis_next(j) > y_axis_old(j)) && ...
62         (y_axis_next(j) > final_y(j)) || ...
63     ((y_axis_next(j) < y_axis_old(j)) && ...
64         (y_axis_next(j) < final_y(j))) )
65
66         x_axis_next(j) = x_axis_old(j) - ...
67             ( $\Delta_d(j)$ )*sqrt(1/(1+slope(j)^2));
68         y_axis_next(j) = slope(j)*(x_axis_next(j) - ...
69             x_axis_old(j)) + y_axis_old(j);
70     end
71 end
72 [a(k) b(k)] = energy_function(Number_of_Nodes, ...
73     x_axis_next, y_axis_next);
74
75     k=k+1;
76      $\Delta_t$  =  $\Delta_t$  + step;
77     status = status - step;
78 %     drawnow
79 %     set(h, 'XData', x_axis_next, 'YData', y_axis_next)
80 end
81 actual_energy(temp) = sum(a)/size(a,2);
82 optimal_energy(temp) = sum(b)/size(b,2);
83 end
84
85 xx = 1:temp;
86 plot(xx, actual_energy, xx, optimal_energy);

```

### A.3 Energy Function

```

1 function [actual_total_energy, optimal_total_energy] = ...
2     energy_function(n, node_x_axis, node_y_axis)
3
4 % clear all;
5 Number_of_Nodes = n;
6 % Define the area
7 x_max = 1000;
8 y_max = 1000;
9
10 %Initialize the neighbors of all nodes to Zero
11 node_neighbors = zeros(Number_of_Nodes,Number_of_Nodes,2);
12
13 % Find the neighbors of each node
14 for i = 1:Number_of_Nodes
15     for j = 1:Number_of_Nodes
16         distance = sqrt((node_x_axis(i)-node_x_axis(j))^2 + ...
17             (node_y_axis(i)-node_y_axis(j))^2);
18         if(distance<250)

```

```

19         node_neighbors(i, j, 1) = 1;
20         node_neighbors(i, j, 2) = distance;
21     end
22 end
23 end
24
25 node_transmission_range = zeros(1, Number_of_Nodes);
26
27 % Find the minimum transmission ranges
28 node_transmission_range = max(node_neighbors(:, :, 2), [], 2);
29
30 % Set the transmission range of neighborless nodes to zero
31 node_transmission_range((node_transmission_range==0)) = 250;
32
33 p = (281*10^-3)*((1000*8)/(54*10^6));
34
35 actual_node_energy = zeros(Number_of_Nodes, 1)+p;
36 optimal_node_energy = ((node_transmission_range.^2))*p/(250^2);
37
38 actual_total_energy = sum(actual_node_energy);
39 optimal_total_energy = sum(optimal_node_energy);

```

#### A.4 Discretized Energy Function

```

1 function [actual_total_energy, optimal_total_energy] = ...
2     energy_function_discretized(n, node_x_axis, node_y_axis, levels)
3
4 % clear all;
5 Number_of_Nodes = n;
6 % Define the area
7 x_max = 1000;
8 y_max = 1000;
9
10 %Initialize the neighbors of all nodes to Zero
11 node_neighbors = zeros(Number_of_Nodes, Number_of_Nodes, 2);
12
13 % Find the neighbors of each node
14 for i = 1: Number_of_Nodes
15     for j = 1: Number_of_Nodes
16         distance = sqrt((node_x_axis(i)-node_x_axis(j))^2 + ...
17             (node_y_axis(i)-node_y_axis(j))^2);
18         if(distance<250)
19             node_neighbors(i, j, 1) = 1;
20             node_neighbors(i, j, 2) = distance;
21         end
22     end
23 end
24
25 node_transmission_range = zeros(1, Number_of_Nodes);

```

```

26
27 % Find the minimum transmission ranges
28 node_transmission_range = max(node_neighbors(:, :, 2), [], 2);
29
30 % Set the transmission range of neighborless nodes to zero
31 node_transmission_range((node_transmission_range==0)) = 250;
32 % Discretization
33 c = 0;
34 for i = 1:levels
35 c = c+(node_transmission_range>i*(250/levels))*(250/levels);
36 end
37 node_transmission_range = c+(250/levels);
38 p = (281*10-3)*((1000*8)/(54*106));
39
40 actual_node_energy = zeros(Number_of_Nodes,1)+p;
41 optimal_node_energy = ((node_transmission_range.^2)*p)/(2502);
42
43 actual_total_energy = sum(actual_node_energy);
44 optimal_total_energy = sum(optimal_node_energy);

```