2016

Game Theoretical Approach for Joint Relay Selection and Resource Allocation in Mobile Device Networks

Runan Yao
South Dakota State University

GAME THEORETICAL APPROACH FOR JOINT RELAY SELECTION AND RESOURCE ALLOCATION IN MOBILE DEVICE NETWORKS

BY

RUNAN YAO

A thesis submitted in partial fulfillment of the requirements for the

Master of Science

Major in Computer Science

South Dakota State University

2016

GAME THEORETICAL APPROACH FOR JOINT RELAY SELECTION AND RESOURCE ALLOCATION IN MOBILE DEVICE NETWORKS

This thesis is approved as a creditable and independent investigation by a candidate for the Master of Science in Computer Science degree and is acceptable for meeting the thesis requirements for this degree. Acceptance of this does not imply that the conclusions reached by the candidates are necessarily the conclusions of the major department.

Manki Min, Ph.D
Thesis Advisor Date

Steven Hietpas, Ph.D
Head, Department of Electrical Engineering
and Computer Science Date

Dean, Graduate School Date

ACKNOWLEDGEMENTS

I would like to express the deepest thanks to my thesis advisor, Dr. Manki Min. He leads me to understand what a reader needs to know and how to express my thoughts onto the paper. He always patiently listens to me when I try to explain myself.

I would like to thank my graduate coordinator, Dr. Sung Shin. His help during my master program makes me stay in the correct path of study. He is knowledgeable, and the course he taught can be used in the whole rest of life.

I also need to thank to my former advisor, Dr. Wei Wang who is now working in San Diego State University. He introduced the wireless communication research to me and encouraged me to explore my own topic.

CONTENTS

ABBREVIATIONS

D2D	Device to Device
WSN	Wireless Sensor Network
WMSN	Wireless Multimedia Sensor Network
CR	Cognitive Radio
ARQ	Automatic Repeat request
MAC	Media Access Control
QoS	Quality of Service
DR	Distortion Reduction
DWT	Discrete Wavelet Transform
ASK	Amplitude-Shift Keying
OOK	On-Off Keying

LIST OF FIGURES

LIST OF TABLES

ABSTRACT

GAME THEORETICAL APPROACH FOR JOINT RELAY SELECTION AND RESOURCE ALLOCATION IN MOBILE DEVICE NETWORKS

RUNAN YAO

2016

With the improvement of hardware, more and more multimedia applications are allowed to run in the mobile device. However, due to the limited radio bandwidth, wireless network performance becomes a critical issue. Common mobile solutions are based on the centralized structure, which require an access point to handle all the communication requirement in the work area. The transmission performance of centralized framework relies on the density of access points. But increasing the number of access points will cost lot of money and the interference between access point will reduce the transmission quality. Thanks to the wireless sensor network implementations, the distributed wireless network solution has been well studied. Now, many mobile network studies introduce the device to device idea which is a distributed structure of mobile network. Unlike wireless sensor networks, mobile networks have more movability and higher transmission speed requirement. In order to be used in mobile networks, a distributed network management algorithm needs to perform faster and more accurate. In this thesis, a new pairing algorithm is proposed to provide a better transmission quality for multimedia data. In the proposed approach, the multimedia data is quantized by distortion reduction. Then, the source-relay pairing solution is optimized by a history tracing system using game theory to improve the

expected overall distortion reduction of the entire network. Several parameters are introduced in the proposed solution, so the optimization would fit for different situations. Simulation results show that the proposed algorithm achieves higher overall distortion reduction by avoiding the competition between nodes. Simulation results also show the parameters would affect the system performance, such as optimization speed, system stability and system overall transmit speed.

1. INTRODUCTION

By means of the low cost and high performance, smart phones and other mobile devices become one of necessities in people's daily life. Thanks to the research in micro-electronics, the performance of hardware has been significantly improved. More and more mobile devices now become multimedia platforms to allow people to watch videos or photos. Not like the computation speed evolution, current cellular network transmission speed has not had significant improvement during the past several years. Due to the limited bandwidth of cellular network transmissions, many application programs only can work with local multimedia data that is already downloaded in the device. In order to play remote multimedia data on the fly, Device to Device (D2D) strategy is introduced into mobile device communications. By introducing the relay strategy in wireless sensor networks (WSN), D2D technique allows devices to transmit data with each other directly. D2D technique does improve the transmission speed of wireless communications, however it is still limited since mobile network has its own feature compared with WSN.

Since many WSN research results can be used or already has been used in D2D network, the background survey in this thesis covered several modern WSN technique. Nowadays, multimedia data is transmitted via wireless network for security issue, such as health care, security and forest fire forecast. Based on the industry requirements and objectives, several challenges and design goals in current WSN research area were introduced in [6] in which the authors believe resource constraints and low-cost are the greatest challenge and the highest goal. As a topic special paper, several techniques that have already been implemented on WSN are introduced in [4]. Two distinct phases of typical wireless sensor network workload control are discovered in [4]. Because of this, shutdown/wakeup becomes a very straightforward solution. Switching the node work mode provides a simple method to improve the energy efficiency [1]. Also based on cycling optimization idea, an adaptive cycling algorithm on energy allocation is introduce in [2]. Some researchers try to solve the problem via cross layer optimization. A preliminary research for this thesis on individual node resource management by investigating the energy assignment and data packet characteristic has been performed [3]. Also the ultra-low power medium access protocols and energy gathering system design are mentioned in [4]. Instead of improving the energy consumption efficiency based on traditional battery-operated sensors, some research starts introducing energy harvesting into their systems. Focuses on existing energy harvesting system, various designing and operating issues and tradeoffs are surveyed in [5]. The harvesting aware power managing techniques are also well discussed in [5][7] and [8]. On the other side, to build a reasonable energy harvesting system, some research starts measuring the energy resource data [12].

Dynamic topologies and harsh environmental conditions, as the second important challenge, require the WSN to have a scalable architecture and an efficient protocol. Even though the individual node power management surely improves the life cycle of the sensor node, the cooperation between nodes is much more important. In [9], a priority-based traffic scheduling approach was proposed to enhance the performance of Cognitive Radio (CR) communication infrastructure to support real-time communication in a smart grid. The authors classified and prioritized different traffic types used in a CR network system, to obtain optimal resource utilization. Also cognitive radios are used in the smart grid communication infrastructures, for example a hybrid smart grid communication framework was proposed in [10] to deal with the challenging environments. The preliminary research for this thesis in [11] was focused on investigating the adaptability of a communication protocol to energy harvesting profiles and a link level network Automatic Repeat reQuest (ARQ) retransmission limit adaptation algorithm was proposed to minimize the cumulative average packet error rate based on the environmental energy availability.

However, traditional mathematical optimization for solving wireless communications encounters many limitations since the mobility brings a high level of complexities and limits the performance of hardware. A highly dynamic and individual decision optimization method is required for further research. Due to this, more and more people start applying game theory on their studies. Some researchers applied game theory on channel management, which is a hot topic in wireless transmission improvement. In [12] the authors presented an overview of different game theory formulations and a survey on these formulations, and then introduced their own non-cooperative game theory formulation which has a solution determined by the Nash equilibrium for the amount of bandwidth offered to a new connection. Based on the solution, the authors wanted to improve the radio resource management on 802.16 type wireless metropolitan area network. Unlike in [12], the approach in [13] is not solving the problem on any specific network protocol. Instead, the authors built their own solution on a generalized wireless network. By applying a grasping money game, they provided a new solution in wireless channel resource allocation. The simulation for two players and multi-players were provided as well in [13].

Along with the focus different from the above papers, research in this thesis is focused on an extremely large scale D2D network, aiming to solve the resource allocation problem with limited communication on system status. The resource allocation problem is mathematically modeled based on the prisoner's dilemma problem, and game theory is applied to compute the solution. Also, machine learning technique is applied on each node to find the Nash equilibrium of the system. Simulation result shows that the proposed solution significantly improves the system's overall transmission quality. Insufficient information, system's lowest transmission requirement and energy restriction will be considered throughout this thesis.

The rest of this thesis is organized as follows. In Literature Review chapter, some useful papers will be reviewed. In Problem Statement chapter, the problem is mathematically formulated as a constraint optimization problem. In System Model chapter, the competition between nodes is discussed and modeled using prisoner's dilemma. Based on the system model, in Nash Equilibrium chapter, an optimization process is found based on Nash Balance and machine learning technique. Then, an algorithm based on the game theory will be proposed. Simulation result will be provided in Simulation and Analysis chapter.

2. LITERATURE REVIEW

In this chapter, several papers and some basic knowledge will be introduced briefly. During the thesis study, these papers provide useful suggestions and surveys.

The main topic of [4] is how to extend the lifetime of wireless sensor network. To extend the lifetime, four research directions have been discussed: hardware level energy saving, protocol level energy saving, energy harvesting and adaptive sampling.

As a keystone paper published on 2006, many solutions mentioned in [4] have already been implemented. The hierarchy hardware architecture is one of those solutions. The basic idea of the solution is using sleep mode to reduce overall energy consumption. There are two goal of this architecture: provide an ultra-low power sleep mode and provide a rapid wakeup capability to minimize. [4]

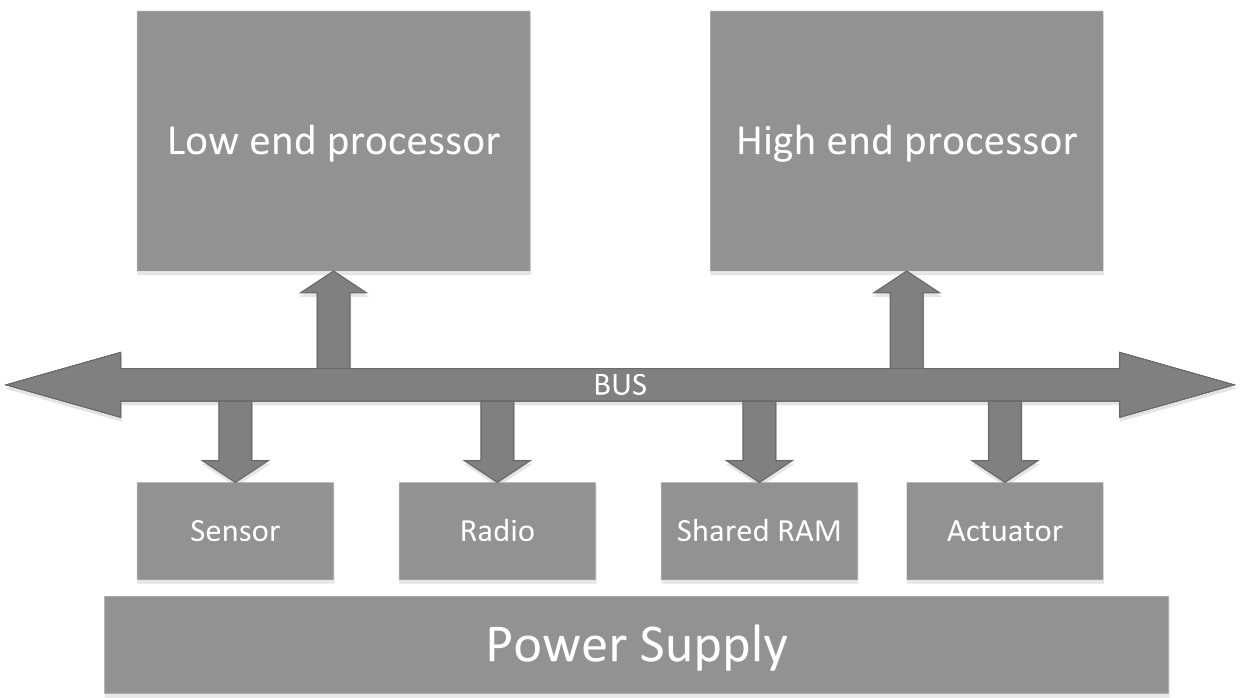

Figure 1. A heterogeneous multiprocessor sensor node with staged wakeup

Figure 1 shows the proposed multiprocessor solution. The processor system is divided into a low end and a high end. The other major parts such as sensors, radios, actuators and the RAM are shared by these two ends. The low end is designed as a low energy consumption system, taking care of the basic system, manages the shutdown and wakeup of the high end. The high end has a powerful hardware which also consumes more power. It only works when system is running in wakeup mode, and provides enough processing speed for the entire system.

This multiprocessor architecture is now used not only in wireless sensor networks, but also used in mobile devices and other wireless network systems. This thesis is also based on this architecture, which assumes that the system will keep low energy consumption when no data packet is being transferred.

The second solution proposed in [4] is optimization in MAC protocol. Not like the hardware chapter, instead of introducing theoretical solution, MAC chapter focuses more on the existing MAC implementation. Several research papers including their implemented MAC protocol have been introduced in this paper, such as B-MAC [15], STEM-T [16], WiseMAC [17] and S-MAC [18]. To minimize the duty-cycling overhead, a model of long-term clock drift is used in UBMAC [19], which is an uncertainty driven approach to duty cycling instead of being completely asynchronous or synchronous. Some of the introduced MAC protocols are now used in different wireless communications.

In this thesis, a cross layer idea is applied into the optimization is applied for network layer and application layer. Since the data link layer is not discussed in our cross layer solution, the MAC protocol which is the part of the data link layer will not be covered in this thesis.

The third solution discussed in [4] is energy harvesting. Now many wireless sensor network have the energy harvesting part which can generate power from nature environment. Since this thesis research focuses more on the battery supplied system, the energy harvesting issue is not a major concern in the proposed solution.

The last direction proposed in [4] is adaptive sampling. There are two different sampling adaptive solution: triggered sampling and model-based active sampling.

Triggered sampling adaptive solution works when a physical event or phenomenon can be sensed with different sensors with different performance-power characteristics. In [4], A vehicular target detection system is used in our former study. In [20], Trigger adapt system also used a low end and a high end to build a sleep/wakeup system which achieves a higher energy consumption.

The key idea of model-based active sampling is that the system learns spatiotemporal relationships among the measurements made by sensor nodes, and uses this knowledge to optimize the sensing for energy (i.e., whether, when, where, and at what fidelity level should a sensor measurement be made) for a required level of overall application-sensing task. [4] The model-based active sampling is a new solution which has no implementation found during the background study.

Adaptive sampling is more related to the sensor, so it is not applied in this thesis research.

[7] provides a better overview about the multimedia researches and implementations on wireless sensor network area. In 2007, when this paper was published, the author already realized multimedia would become an important area. As claimed in [7], the focus is shifting toward research aimed at revisiting the sensor network paradigm to enable delivery

of multimedia content, such as audio and video streams and still images, as well as scalar data.

The first contribution of [7] is to reaffirm that a multimedia network should be evaluated by the quality of service (QoS). Unlike the traditional dataset, multimedia data packets always have different priorities. So, the way of evaluating a network cannot be done simply by counting the throughput or the latency. Instead, most potential applications of a WMSN (Wireless Multimedia Sensor Network) require the sensor network paradigm to be rethought to provide mechanisms to deliver multimedia content with a predetermined level of quality of service (QoS). [7] In this thesis, the QoS happens not only between different applications, but also between different data packets in the same application.

In [7], several applications are listed which using wireless network to transmit multimedia data, such as Multimedia Surveillance Sensor Networks; Traffic Avoidance, Enforcement, and Control; Advanced Health Care Delivery; Industrial Process Control. Since there are almost ten years after this paper published, many mentioned applications are already being used in daily life. Now traffic lights are all controlled by the traffic monitor sensor, that allows the lights changing based on the traffic. Many people use smart watches or sports bands which are connecting to their cell phones and then transmit data into the cell phone network. Figure 2 shows a more common situation how we are using the smart phones and other related equipment. This network is called personal wireless network whose prototype is also mentioned in [7].

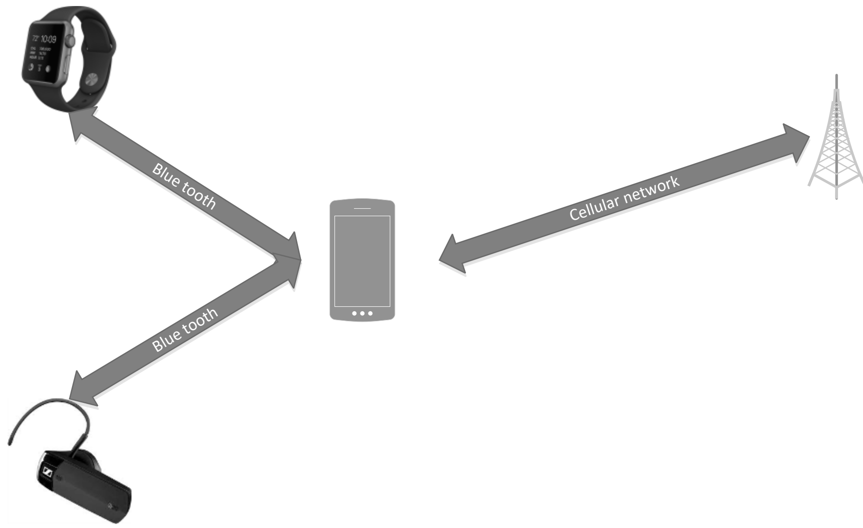

Figure 2. Personal Wireless Network

Also, an energy harvesting embedded architecture was introduced in [7] for wireless multimedia sensor network. However, this architecture focuses more on the hardware part, and is not adopted in this thesis research. The most useful information in [7] for this thesis study comes from the Factors Influencing Design of Multimedia Sensor Networks chapter. In this chapter, Cross-layer technique, Application-specific QoS [21] and Multimedia In-network Processing are introduced in detail. The authors mentioned "the QoS required by the application will be provided by means of a combination of cross-layer optimization of the communication process and in-network processing of raw data streams that describe the phenomenon of interest from multiple views, with different media, and on multiple resolutions. Hence, it is necessary to develop application-independent and self-organizing architectures to flexibly perform in-network processing of multi-media contents." This is also a key policy followed in this thesis.

Based on layer solutions, there are also several techniques based on traditional layer solution listed in [7]. The UWB technology for physical layer which is proposed in [22] is able to provide a low power consumption, high data rate network within an acceptable range. The link-layer error control related technology for MAC layer introduce the gain and cost of re-transmission process. [23]

The network traffic is categorized into several classes in [7], which is listed in Table 1.

Table 1. Traffic Classes

Class type	Data type	Bandwidth	Description
Real-time, loss-tolerant	Multimedia	High	Multilevel streams composed of video/audio and other scalar data (e.g. temperature readings), as well as metadata associated with the stream, that need to reach the user in real time
Delay-tolerant, loss-tolerant	Multimedia	High	Streams intended for storage or subsequent offline processing that need to be delivered quickly due to the limited buffers of multimedia sensors
Real-time, loss-tolerant	Data	Moderate	Monitoring data from densely deployed scalar sensors characterized by spatial correlation or loss-tolerant snapshot multimedia data (e.g., images of a phenomenon taken from multiple viewpoints at the same time)
Real-time, loss-tolerant	Data	Moderate	Data from time-critical monitoring processes such as distributed control applications
Delay-tolerant, loss-intolerant	Data	Moderate	Data from monitoring processes that require some form of offline post processing
Delay-tolerant, loss-tolerant	Data	Low	Environmental data from scalar sensor networks or non-time-critical snapshot multimedia content

Another guiding paper that used in the thesis study, [8], has the same author of [4]. Compared with [4], [8] focused more on the energy saving than on energy harvesting. Even though [8] is published earlier than [4], it has more useful knowledge than [4] since this thesis is based on a wireless sensor network with no energy harvesting.

The first major contribution of [8] is to figure out that the major energy consuming part of a wireless device is the processor and radio. According to [8], the processor consumes 36% of the battery and radio consumes 62% of the battery. A sensor, somehow only consumes 0.6% of the battery. However, this study is based on a traditional wireless sensor node, which means the sensor may have limited function which leads to a low energy consumption. But, as reported by later study, radio and processor still consumes most of the power in multimedia wireless devices.

As a result of study above, the radio power management is found to be critical in wireless communication. Based on this, the power consumption of an RFM (Radio Frequency Monitor) radio is well studied. According to the result, an RFM radio would consume more power in a high transmission speed than in a low transmit speed. But the power consumption is not a linear relationship with transmit speed. Also, an RFM radio would consume more power in ASK (Amplitude-Shift Keying) mode than in OOK (On-Off Keying) mode.

The packet forwarding issue is also introduced into wireless network study in [8], which is also the main topic of this thesis study. The study result of [24] showed almost 65% of all packets a sensor node received need to be forwarded. An energy-aware packet forwarding architecture is proposed in [24]. This architecture allows packet forwarding via communication system without waking up the main control system. The difference is shown in Figure 3.

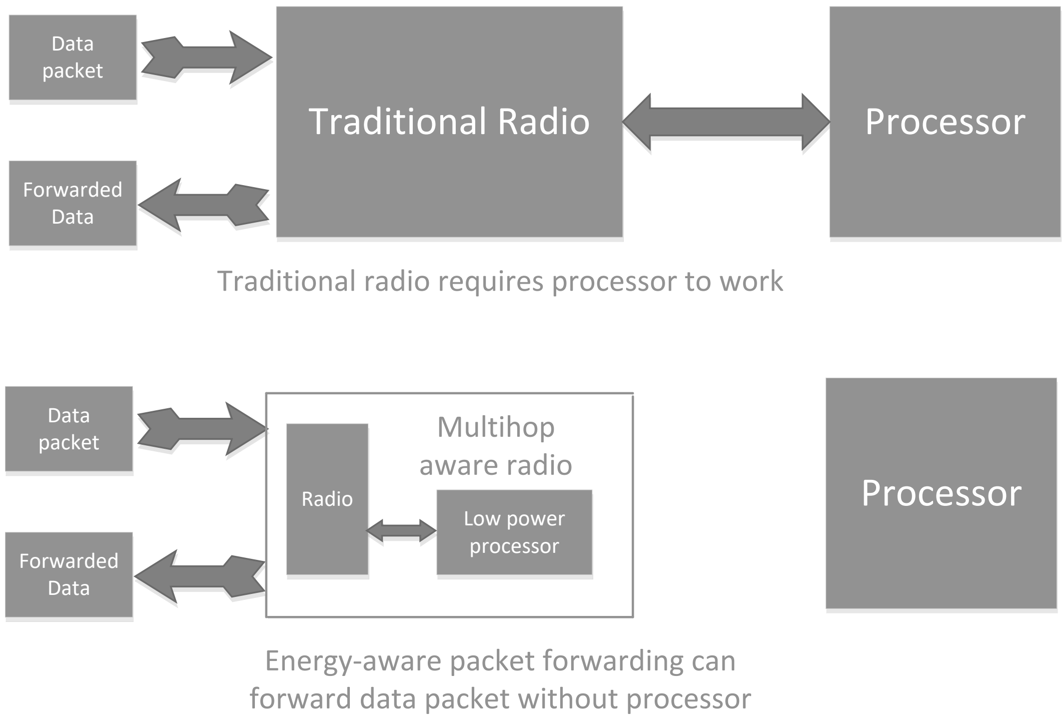

Figure 3. The difference between traditional radio and energy aware packet forwarding radio

The radio technology used in wireless communication is also discussed in [8]. Considering the radio modulation, radio startup energy cost and packet header, an energy consumption equation based on constant bit error rate system [25] [26] is introduced as follow:

$$E_{bit} = \frac{E_{start}}{L} + \frac{P_{elec} + P_{RF}(M)}{R_s \times log_2 M} \times \left(1 + \frac{H}{L}\right)$$

In this equation, E_{bit} denotes the energy consumption of each bit in the data packet, E_{start} denotes the radio startup consumption, M denotes the modulation, P_{elec} denotes the energy consumption power of processing system, the $P_{RF}(M)$ is a function to calculate the power of radio system to keep the bit error rate when modulation changed, R_s denotes the transmit rate under modulation M, H denotes the header size, L denotes the payload size.

This equation is simplified and used in the simulation chapter. The simulation is performed with fixed modulation, system power consumption and the packet length. So, when running simulation in this thesis study, energy cost is equal to the data packet sent out.

The most important idea [8] introduced is traffic distribution. Since all data packet need to be forwarded to the destination, a straight-forward solution of energy saving is to find the most energy efficient multi-hop route to transmit the data packet. Aiming on the selection of the lowest energy cost route, [27,28,29] provide different approaches. However, lowest energy cost route strategy cannot maximize the lifetime of the overall network [30]. In this thesis study, extending the lifetime of the overall network is one of the objectives as well. Some other topics in [8] are also considered during the research study of this thesis, such as, computation communication tradeoffs and topology management.

In this thesis study, the network performance is evaluated by Distortion Reduction (DR). The concept of DR comes from the wavelet transform, in computer science, which is called discrete wavelet transform (DWT). DWT is a common algorithm used in image or video compression. A one level DWT will transform original image into four pieces, which is called LL1, HL1, LH1, HH1. In which LL1 can do another DWT, and get LL2, HL2, LH2, HH2. This is called a two level DWT. Figure 4shows a one level DWT sample. The image can be decompressed even any of the four pieces is lost.

The loss of pieces will bring the distortion which means the difference between original image and the depression result. Figure 5 shows the different results of losing one of the piece. It is not hard to see, the distortion of losing each piece is significantly different. In real applications, DWT will be performed in multiple levels and saved in data packets. So loss of different data packets will gain different distortion. So, the distortion will be reduced by receiving a data packet.

Figure 4. A one level DWT

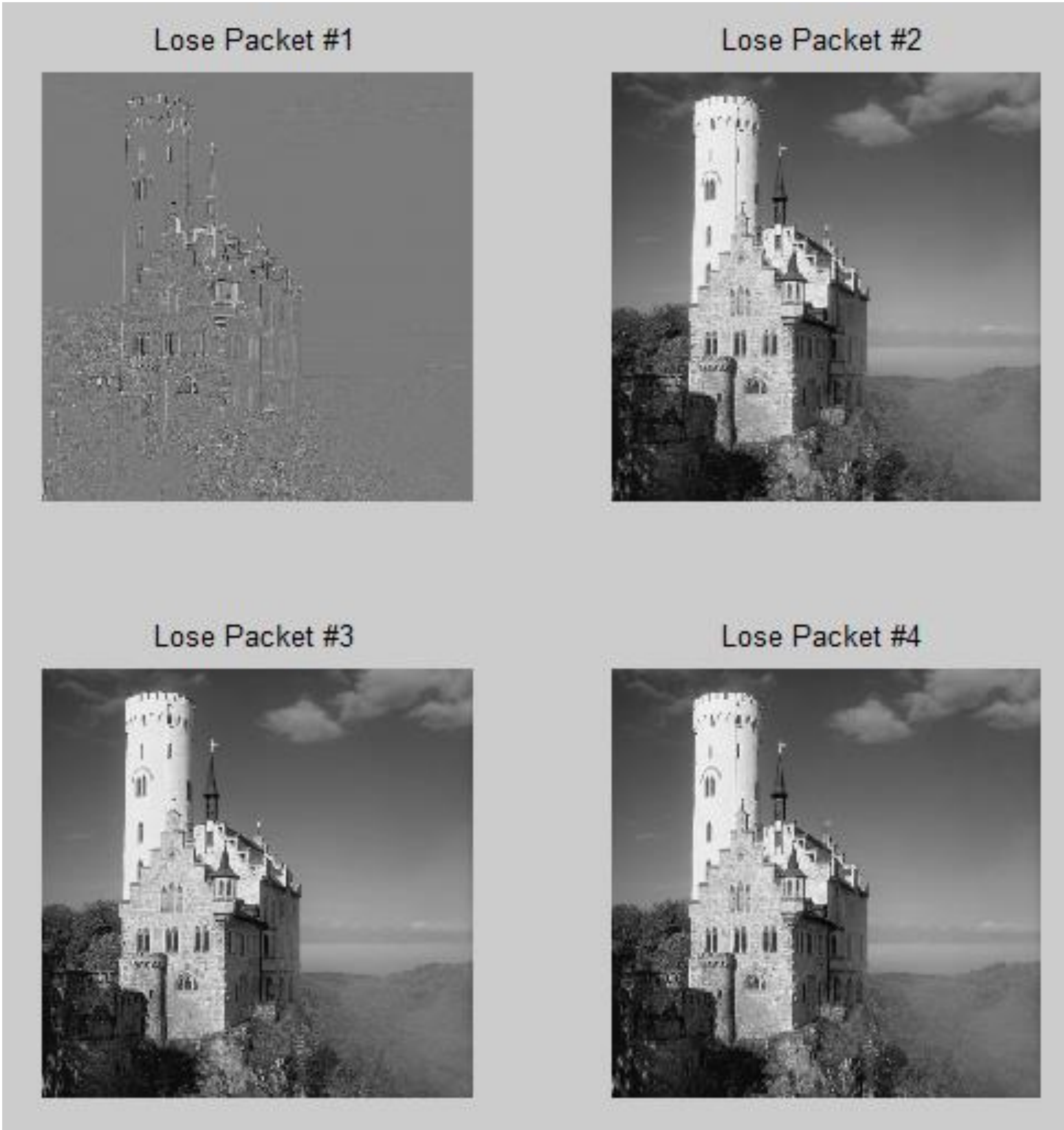

Figure 5. Result of losing LL1, HL1, LH1, HH1

3. PROBLEM STATEMENT

As mentioned above, the source node and relay node can only share their information to a limited number of nodes. Each node has its own strategy to send or relay data packets. The problem is to achieve the maximum sum of reductions of distortion in the entire network by consuming the limited amount of power. The overall problem can be mathematically formulated as a data packet relay strategy problem with energy neutrality constraint for each node:

$$\{S_i\} = argmax\{E[D]\}$$

s.t.

$$E_k \leq \Omega_k, \text{where}$$

S_i denotes the route of data packet i, $E[D]$ denotes the expected distortion reduction of the whole system, E_k denotes the energy consumption of node k, Ω_k denotes the battery capacity of node k. For any node, its energy consumption should be lower than a certain value ($E_k \leq \Omega_k$).

Assume each data packet has same packet length and only counts the data packet sending energy cost. For either sensor node or relay node k, let Υ_k denote the packet transmission energy consumption, then the energy consumption can be formulated as

$$E_k = \Upsilon_k * \sum_i Count(k\ in\ S_i)$$

Let Λ_i denote the transmission expectation of the data packet x, then overall transmission quality can be formulated as:

$$E[D] = \sum_i \Lambda_i$$

Where $\Lambda_i =$

$$\begin{cases} 0 & if\ the\ last\ element\ of\ S_i\ is\ not\ a\ destination \\ DR_i * \prod \rho_u & if\ the\ last\ element\ of\ S_i\ is\ a\ destination \end{cases}$$

Here, DR_i denotes the distortion reduction of data packet i, ρ_u denotes the transmit success rate of the u-th transmission when transmit data packet i.

Table 2. Symbol List

Symbol	Meaning
S_i	Transmit route of data packet i
$E[D]$	Overall system expectation of transmission quality
E_k	Energy consumption on node k
Ω_k	Energy capacity on node k
Υ_k	Packet transmission energy consumption on node k
Λ_x	Expectation of transmission quality of packet x
DR_i	Distortion reduction of data packet i
ρ_u	Transmit success rate of the u-th hops

4. SYSTEM MODEL

In this chapter, the relationship between relay nodes and sensor nodes will be modeled. By analyzing the pairing solution, it is easy to figure out any node in the wireless network would have the prisoner's dilemma issue.

In a traditional wireless network, nodes always try to select the best option in all possible selections. For a sensor node, it always picks the most reliable relay node for relay. For a relay node, it always relays the highest distortion reduction data packet. However, this greedy strategy leads the wireless network always stay in a competition environment.

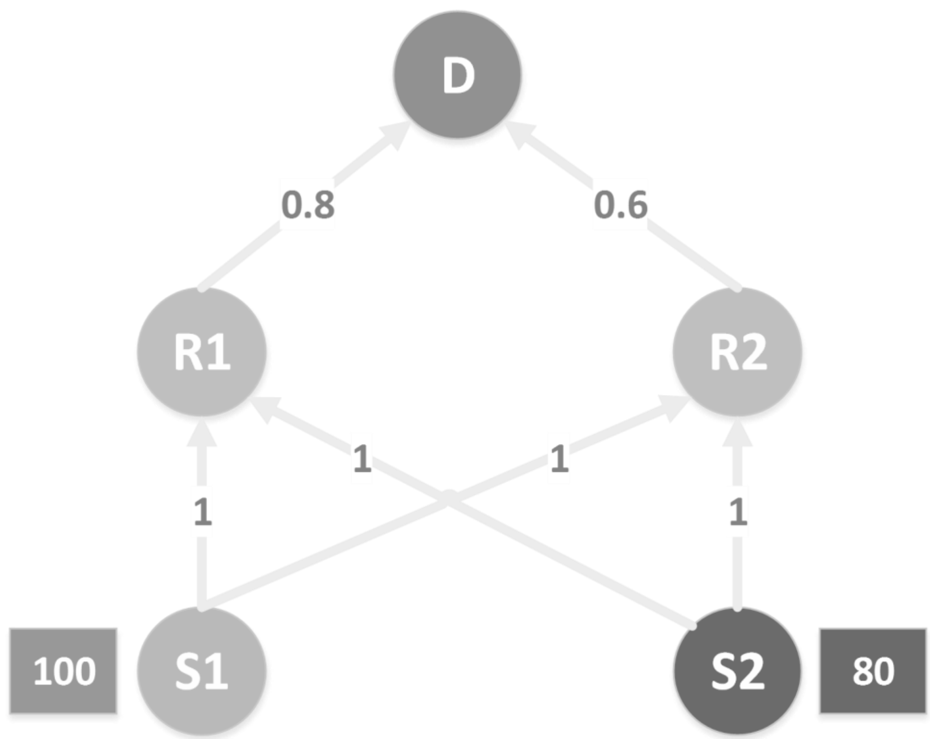

Figure 6. Simply Wireless System

Figure 6shows a simplified wireless system. In this system, there are two source nodes S1 and S2; two relay nodes R1 and R2; one destination node D. S1 has a data packet with distortion reduction value of 100 and S2 has a data packet with 80 distortion reduction. Transmit success rate is shown on each arrow. Assume each source can transfer its data packet to only one relay node, and each relay node can only relay one data packet to destination.

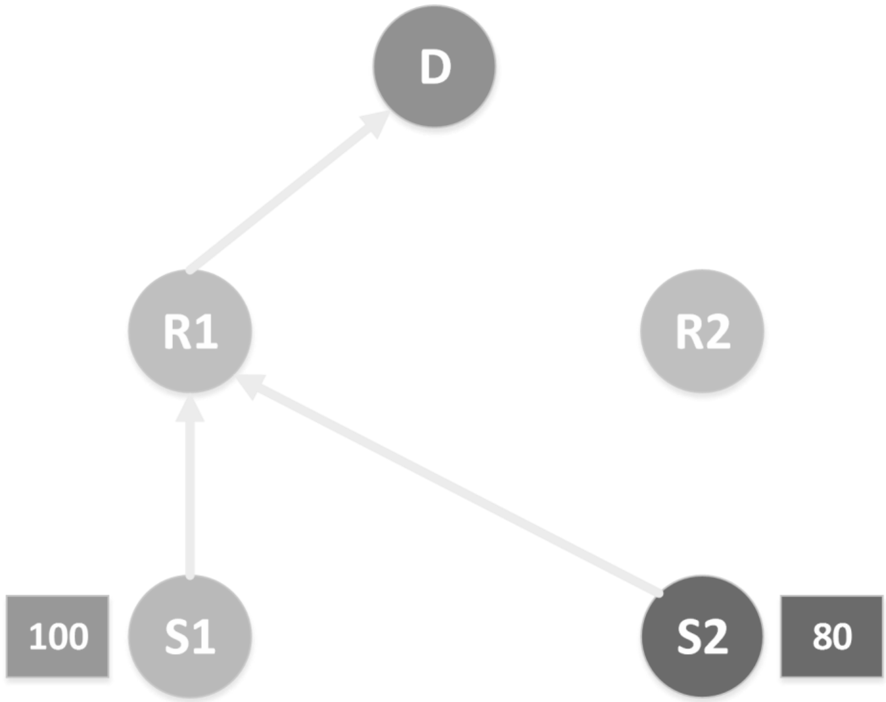

Figure 7. Source Node Selection

Consider the path transmit success rate, S1->R1->D is 0.8, S1->R2->D is 0.6. So R1 is a better relay for S1. Same thing happens in S2. As a result, both S1 and S2 pick R1 for relay. As shown in Figure 8.

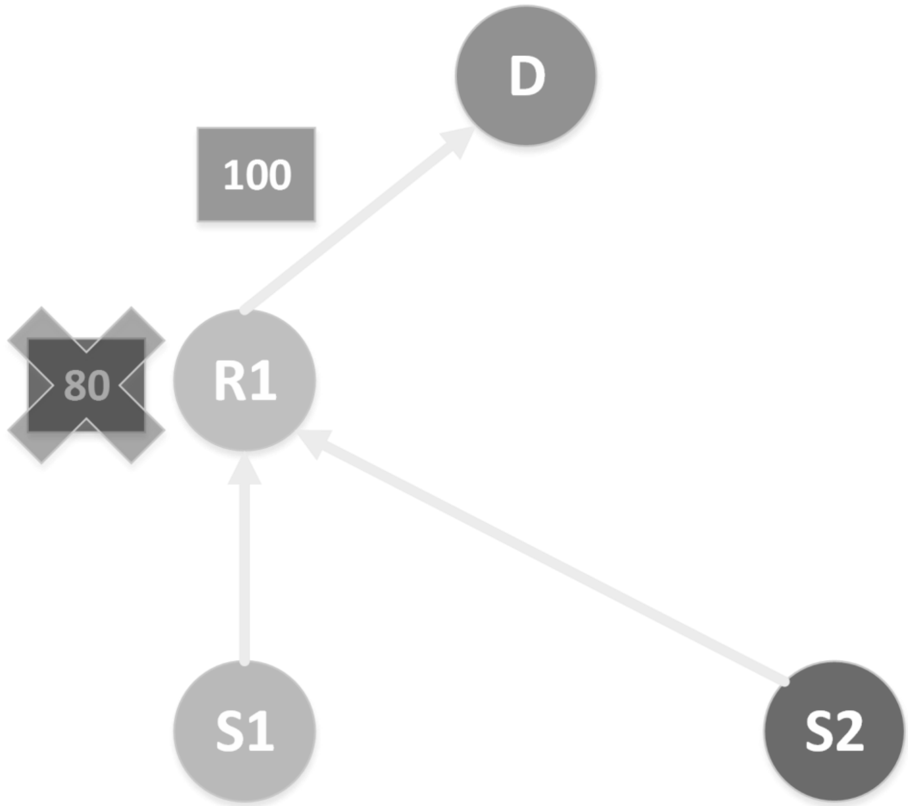

Figure 8. Relay Node Selection

Since the data packet from S1 has a higher distortion reduction than data packet from S2, discard the data packet from S2 and relay the data packet from S1 to D.

In the next chapter, the competition relationship will be built and the optimization solution will be determined based on the Nash Equilibrium idea.

5. NASH EQUILIBRIUM

As mentioned in last chapter, the problem can be formulated as a trade mode. For each node, sending or relaying a data packet turns into a gain and cost problem. Each problem has several values that need to be considered. The final objective is to find the Nash Equilibrium between them.

5.1 Gain in the Trade

The gain of sending/relaying a packet is the expected contribution of the data packet. It can be formulated as the data packet contribution and the data packet transmission success rate.

a. Data packet contribution

In different areas, the contribution of a data packet can be different. In this thesis, the discussion is focused on the image data. The wavelet transform is a common solution in any image compression or transmission. After wavelet transform, one image will be split into a chain of several data packets. The data packets near the head of this chain will have a higher contribution.

b. Data packet transmission success rate

The data packet transmission success rate is an expected value. It indicates the possibility of a data packet being successfully received and decoded. Since wireless communication may bring error bits into the data packets, most application will apply redundant data to do the verification and error recovery. Theoretically, a success rate can be calculated based on antenna power, environment noise, transmission distance and encoding algorithm. In this thesis, the data packet transmission success rate will be calculated based on the final simulation result which is based on a large number of test.

5.2 Cost in the Trade

The cost of sending/relaying a packet can also be formulated as two parts: current node cost and the remaining cost. Current node cost is the cost of sending a data packet from the current node. It can be simply calculated from the data packet length. The remaining cost is the sum of all the costs after the current node until the final destination. It is the feedback from neighbor nodes. And the feedback is calculated and replied by the receiver.

Unlike gains, cost is a set of different types of value. It contains the cost of time, the cost of energy, the cost for channel and the cost of space.

a. Transmission time cost

Theoretically speaking, transmission time has a linear relationship with the data packet length. Practically, common solution of wavelet transform will provide same size data packets. So, the actual transmission time won't be discussed in this thesis, instead, the transmitted data packets will be counted as the time cost.

According to classical Time Division Multiple Access (TDMA) system, the transmit time frame is divided into time slots. In each time slot, node can transmit one or several data packets. However, if a node is holding this slot, the other nodes that may cause interference must keep silent. It means, the transmission time cost is not for the current node, and the numbers in radio silence need to be counted as well.

b. Transmission energy cost

In an overall optimization system, it is required to find the overall transmission energy cost. However, in a relay wireless network, it is very complex. The reason is overall transmission energy cost required the implementation aware of which route the data packet will be used and all energy cost in this route. However, it is not required and useless in a distributed system. In a distributed system, more concern is paid on the energy cost of the current node and the neighbor nodes. Since the transmission energy cost is much higher than standby energy cost, the system standby energy cost is ignored in this thesis.

In this chapter, all elements that are used in the optimization are listed. These elements work together and turn the original problem into an optimization trade problem. Since wireless transmission noise is very high and wireless connections are frequently changed, the elements cannot be quantized directly. In the next chapter, some solutions would be used to evaluate these elements. Then the optimization algorithm will be built using the quantized transmission cost and gain.

6. PROPOSED ALGORITHM

In the previous chapter, all elements are listed that are involved in the proposed optimization. In the proposed framework, some of them will be obtained via traditional ways, which is proposed and recognized as a formal solution; some of them will be calculated via some new solutions. Working coordinately, these solutions successfully provide a self-organized network with optimized transmission pair selection mechanism.

As shown in Figure 3, selecting the best relay node does not always produce the highest overall transmission result. The best overall transmission result will be achieved when nodes found the best matches. Based on this fact, an optimized pairing algorithm will be provided to help the network setup and automatically organize.

There are two parts in proposed algorithm: Initialization and Game Theoretical Progressive Optimization.

Initialization runs when the network is built up. Based on the scale of the system, it may take a few seconds to several minutes. Since the proposed Game Theoretical solution is a transmission-history-based algorithm, the optimization can only run when system already starts transmitting and have some history record for optimization. The main purpose of Initialization is to build up the required data structure, to initialize pairing status and start the transmit, in other words, to provide everything need to start the optimization. The data structure built during Initialization is shown in Figure 4. This data structure includes three lists: Neighbor List, Upper Bracket Relay List and Lower Bracket Relay List. Neighbor List is a traditional neighbor table which is commonly used in wireless transmit. Upper Bracket Relay List and Lower Bracket Relay List are created for storing useful history record.

Since the proposed Game Theory solution is a progressive algorithm, a better start point will help the system reach the highest performance faster. So, Initialization is not only creating a start point, but also try to create a higher performance start point. To achieve a higher performance, some algorithms proposed in my former papers ([3,6,9]) are introduced in this thesis. Using the battery capacity, system energy consumption, signal strength and data packets distortion reduction, nodes will initially select which node to transmit data packets.

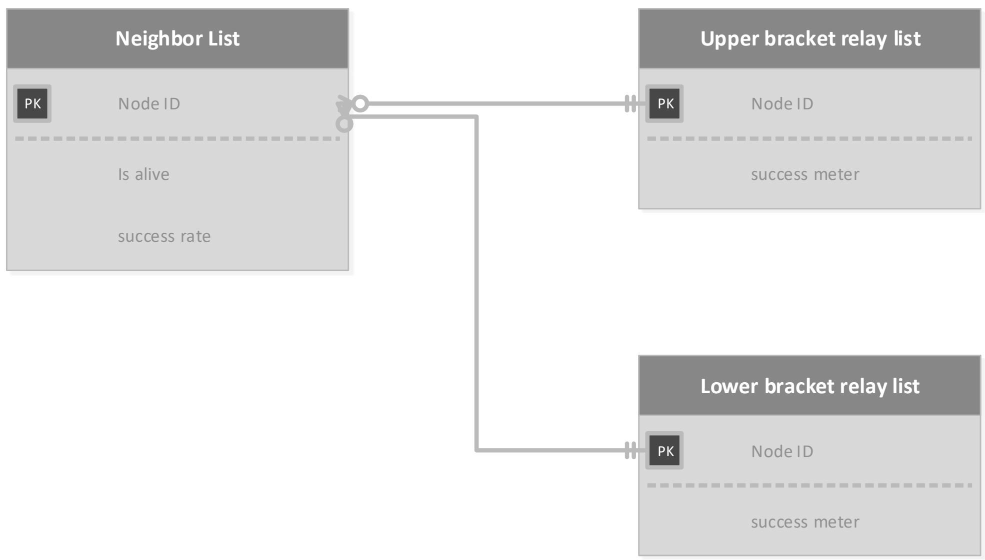

Figure 9. Data Structure for optimization

Game Theoretical Progressive Optimization runs when Initialization is done for all nodes. It will keep running until the system becomes dead. In the optimization, Sender and Receiver as two roles are introduced to replace the classification based on Source, Relay and Destination. Based on the character, each node will be assigned one or two roles. All source nodes will become Sender; the destination node will become Receiver; all relay nodes will become both Sender and Receiver. Each transmit cycle is divided into three major phases: Neighbor ACK phase, Pairing and Transmit phase, Packet Optimization phase. Different roles will perform different actions in each phase. The overall timeline is shown in Figure 5.

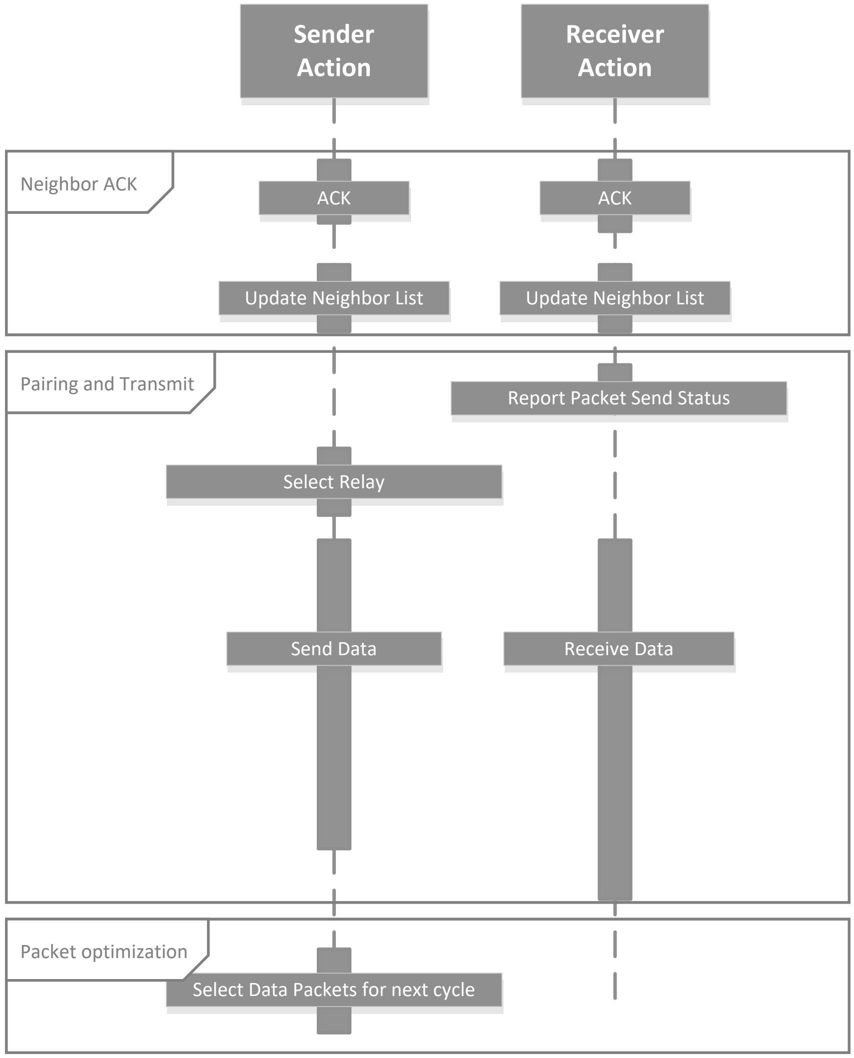

Figure 10. Time line of each role

As same as traditional wireless transmit protocol, ACK acts at the beginning of a transmit cycle to check node alive and refresh the node list table. In neighbor ACK phase, both sender and receiver would send a ACK package with their own identification information. Using the ACK package, each node maintains its neighbor node list to get ready to enter the next phase. At the beginning of Pairing and Transmit phase, sender would get the transmit result report of last transmit cycle from receivers. Based on whether the data packet is successfully relayed or not, neighbor nodes will move between Upper Bracket Relay List and Lower Bracket Relay List. After alternative the two relay lists, the sender will select nodes from both list, assign data packet, and send the data packet. Simply speaking, the Pairing and Transmit phase is for the sender to choose the receiver proactively.

In the packet optimization phase, senders would select data packets that need be sent out in the next transmit cycle. Even though the packet selection algorithm is simply choosing the higher data packets, it has different meaning for different types of nodes. There are two ways to get a data packet that need be sent out: source node generates a new data packet or relay node receives a data packet. For the source nodes, packet optimization is improving the distortion reduction of all data packets that will be involved into the transmit. For the relay nodes, packet optimization is for the receiver to choose the sender nodes proactively. As mentioned above, in pairing and transmit phase, the sender selects receiver by sending the data packets; in packet optimization phase, the receiver selects the sender by choosing its data packet. By choosing each other, the sender-receiver pair is built between sender and receiver. Since the packet optimization is a sorting based on distortion reduction which is pretty straightforward, the key of pairing would be the procedure of maintaining Upper Bracket Relay List and Lower Bracket Relay List in Pairing and Transmit phase.

As shown in Figure 4, all neighbor nodes are assigned into either Upper Bracket Relay List or Lower Bracket Relay List. The Upper Bracket Relay List contains the relay nodes which has a higher possibility to receive and relay data packets. The count of nodes in Upper Bracket Relay List should keep in a low value. The rest neighbor nodes are staying in

Lower Bracket Relay List. Most of the time, the system will pick up the relay nodes from Upper Bracket Relay List, however, sometimes the relay nodes will also be picked from Lower Bracket Relay List in order to find any better nodes. The procedure is shown in Figure 6. Figure 6 only shows the Pairing and Transmit phase. Even though Figure 6 covers two transmission cycles, it will not show any ACK neighbor or Packet Optimization action. The changeable parameters used in the procedure are listed in Table 3. By changing the parameter listed in Table 3, the proposed algorithm will have different characteristics.

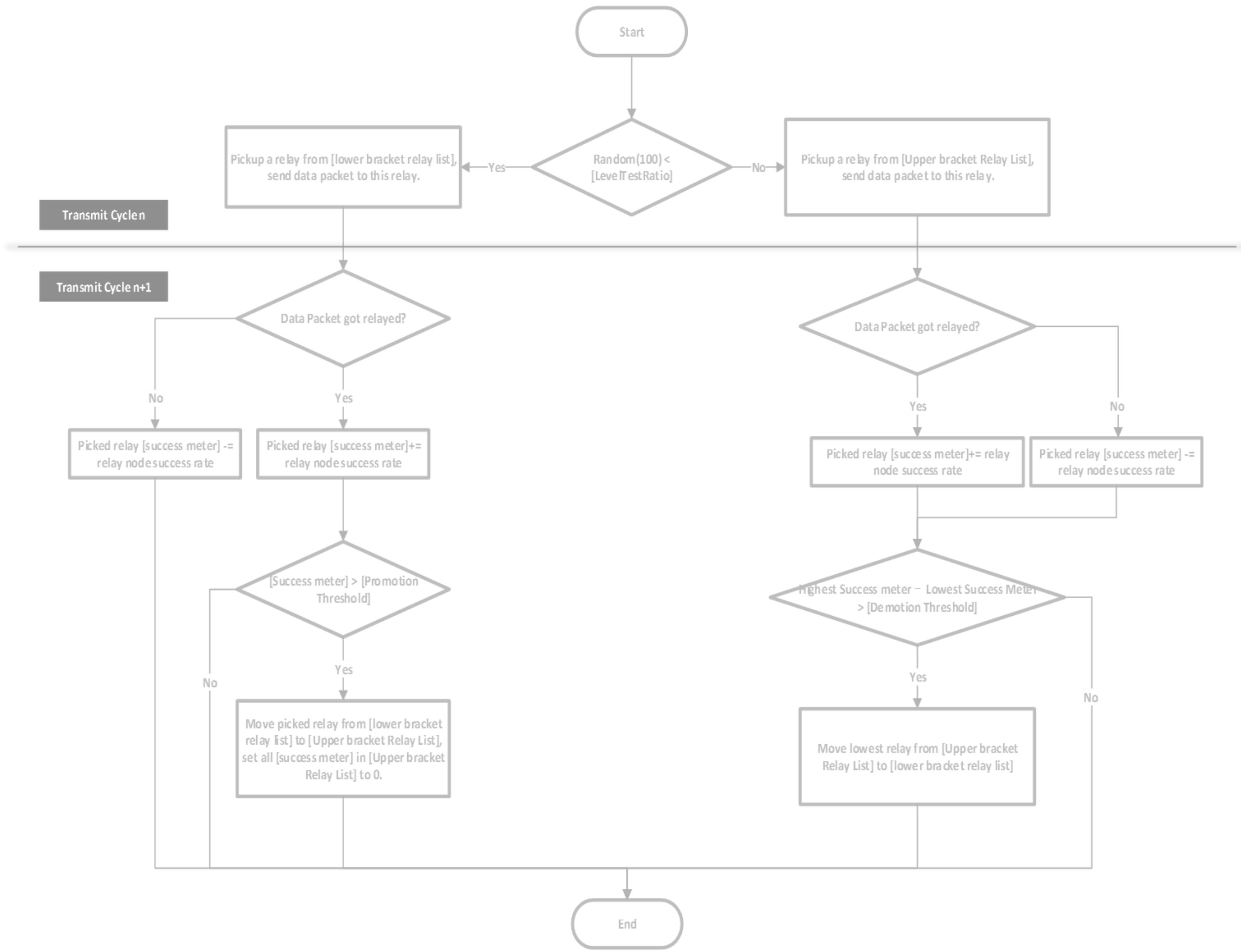

Figure 11. Procedure of Maintain relay lists

Table 3. Parameters

Parameter	Meaning
Level Test Ratio	The chance of sending a packet using Lower Bracket Relay List
Demotion Threshold	The threshold of moving a node from Upper Bracket Relay List to Lower Bracket Relay List
Promotion Threshold	The threshold of moving a node from Lower Bracket Relay List to Upper Bracket Relay List

For each pending data packet, system will decide which Relay List to be used. The chance is controlled by a parameter called Level Test Ratio. If the data packet got relayed successfully, the success rate will be added into success meter of the relay node, otherwise, the success rate will be deducted from success meter. If relay node is picked from Lower Bracket Relay List and the success meter is greater than Promotion Threshold, the relay will be moved from Lower Bracket Relay List to Upper Bracket Relay List. If a relay node is picked from the Upper Bracket Relay List and the success meter is lower plus Demotion Threshold is lower than highest success meter, the relay node will be moved to Lower Bracket Relay List.

The promotion process is an accumulation process, any node flocking enough success meter would be able to send to Upper Bracket Relay List. The demotion process is a competition process. Any node cannot catch up with the highest node will be demoted into the Lower Bracket Relay List.

In the next chapter, the simulation will run under different environment. The effect of each parameter also will be studied.

7. SIMULATION AND ANALYSIS

In this chapter, we provide two common relay strategies and compare with our algorithm. The first strategy collects all information of the system status and build up the solution by enumerating all the possible combinations. Here we call this algorithm "Exhaustive Algorithm". The pseudocode is in Table 4. The other strategy commands each node to pick up the best relay according to transmission success rate. Here we call this algorithm: "Greedy Algorithm".

Table 4. Exhaustive Algorithm

1. S = Set of all possible Source Relay pair. 2. Find $S_1 \cdots S_k$ which are subset of S, such that Si has only non-overlapping pairs for all $1 \leqslant i \leqslant k$. 3. Calculate DR_i as the Expected Distortion Reduction of S_i, where $1 \leqslant i \leqslant k$ 4. Find the max DR_{max} 5. The related set S_{max} is the pair solution

Table 5. Greedy Algorithm

Source:

Func selectRelay()
{
    return RelayList.SortByErrorRateDesc().GetFirst();
}

Relay:

Func selectPacket(){
    return receivedPacketList.SortByDR().GetFirst();
}

Simulation Overall Setup

The simulation runs in a ten by ten nodes array with four destinations in each corner. Each destination can cover ten nodes.

For each node, battery setup follows a normal distribution with mean equal to 150,000 transmissions and standard deviation at 2,000 transmissions. Ten data packets are in the memory when node start, each transmit cycle, a new data packet will be generated by the node. The distortion reduction of each data packet is evenly distributed from 40 to 60.

Packet transmission error rate is defined by constant error rate and dynamic error rate. Constant error rate is fixed at around 0.05 to 0.175, when node initialized. Constant error rate is used to show the hardware effect on the packet transmit error rate. Dynamic error rate is around -0.05 to +0.075, change and applied every transmit cycle. Dynamic error rate is simulating the environment interference.

Every transmit cycle a node can transmit at most 10 data packets. The limit also depends on the battery.

7.1 System Performance Under Normal Situation

In simulation 1, the system starts and runs until nodes are all dead. Game Solution, Greedy, Exhaustive will be simulated. The main purpose of this simulation is to check the static performance of each algorithm.

The parameter for Game Solution is listed in Table 6. The system output over time result is shown in Figure 12, the statistic result shows in Figure 13.

Table 6. Game Solution parameter for Simulation 1&2

Parameter	Value
Level Test Ratio	15%
Demotion Threshold	10

Promotion Threshold	10

According to the test results, even though the proposed game theory pair solution cannot beat the Exhaustive solution, it still achieves a high enough performance with a better stability compared to Greedy solution. Figure 12 shows, the proposed solution uses 250 transmit cycles to do the optimization, which is an acceptable time cost in real problem. Figure 13 shows, the proposed solution produces twice as good as output of Greedy solution.

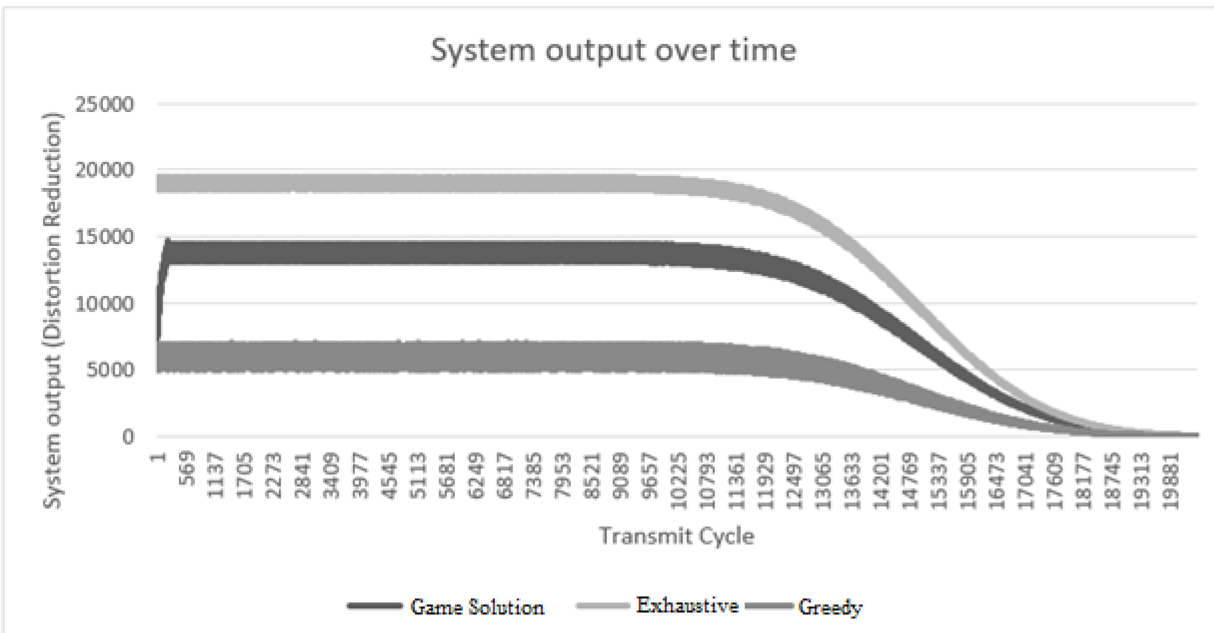

Figure 12. System output of Simulation 1

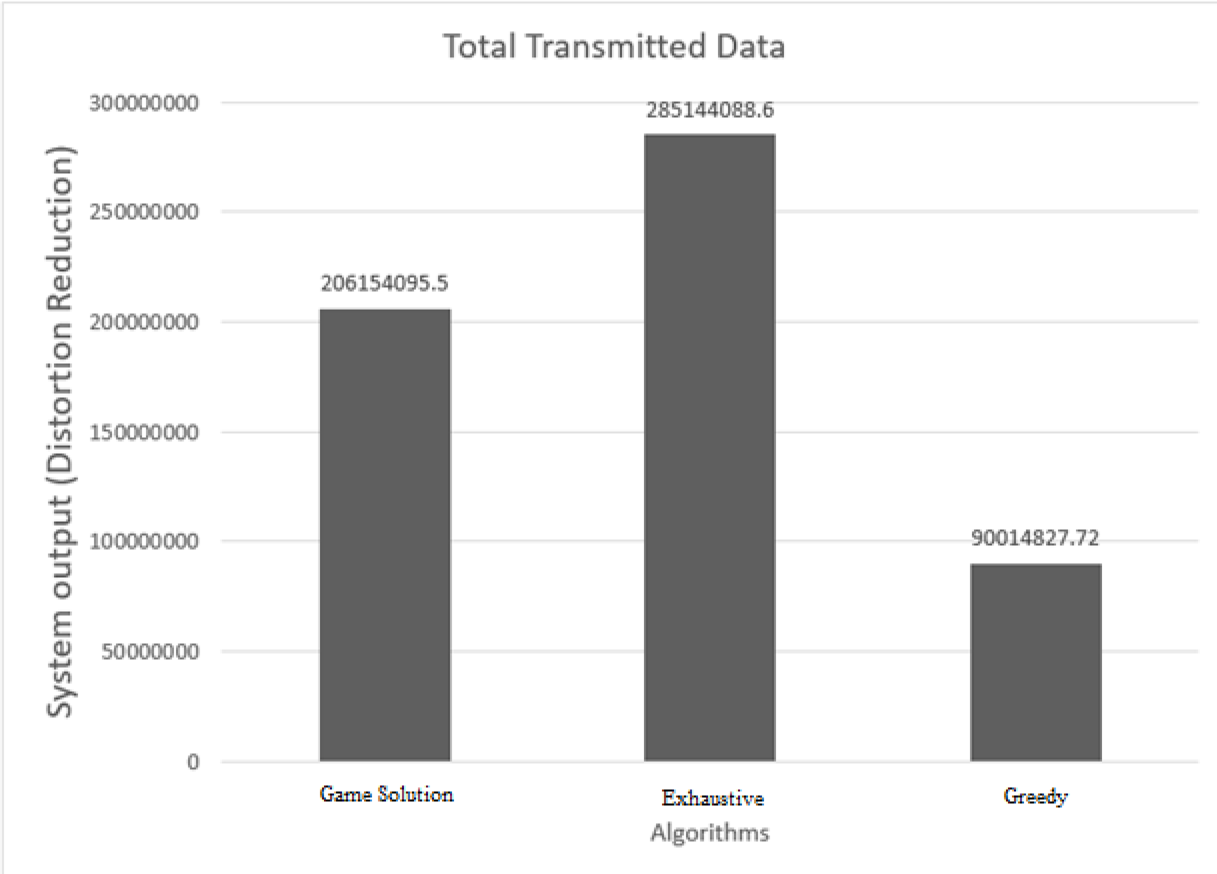

Figure 13. Overall system output of each algorithm in simulation 1

7.2 System Performance When Multiple Nodes Suddenly Dead

In simulation 2, the system starts normally and 15 nodes are manually turned off at transmit cycle 7000. Game Solution, Greedy, Exhaustive will be simulated. The main purpose of this simulation is to check the dynamic performance of each algorithm.

The parameter for Game Solution is as same as Simulation 1, which can be found in Table 6. The system output over time result is shown in Figure 14, the statistic result shows in Figure 15.

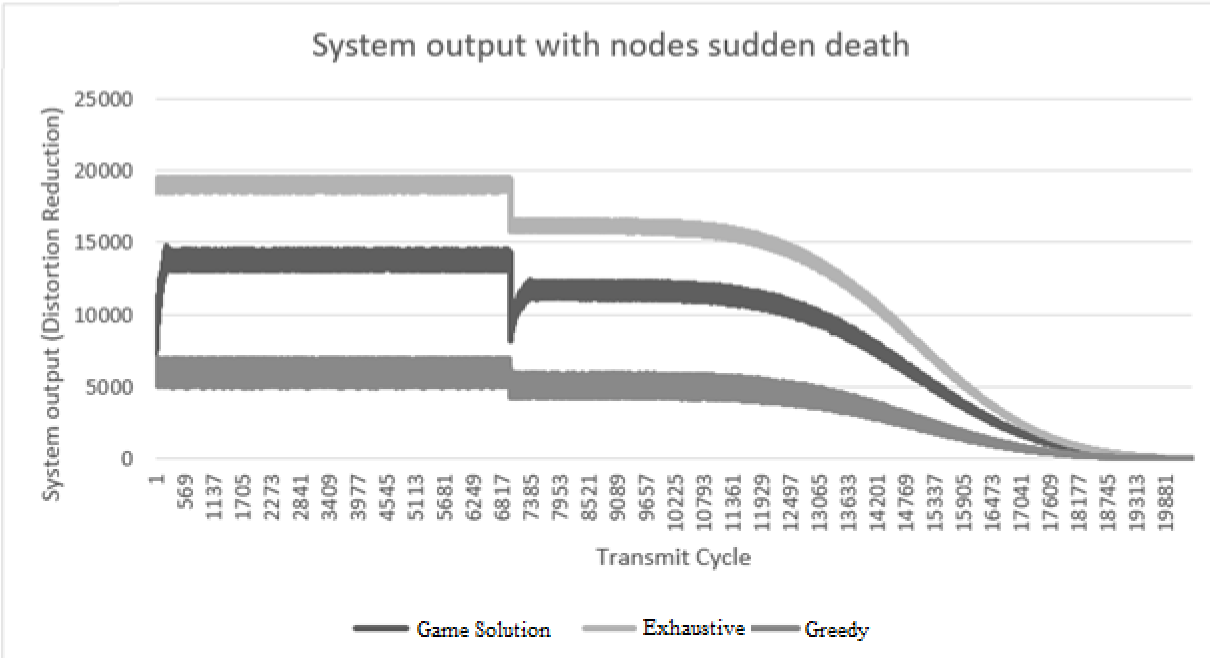

Figure 14. System output of Simulation 2

According to Figure 14, all algorithms have a cut back when several nodes suddenly dead. In this three algorithms, proposed game theory solution has the most decrease. However, the solution can recover some performance after several transmit cycles. Another thing need be noticed is that the recovery time is higher than system initial optimization time. And it shows that the proposed algorithm gets negative impact from the historical record when system is having large change.

According to Figure 15, even though the proposed algorithm needs some time to recover from the impact of system change, the overall performance is still much better than Greedy solution.

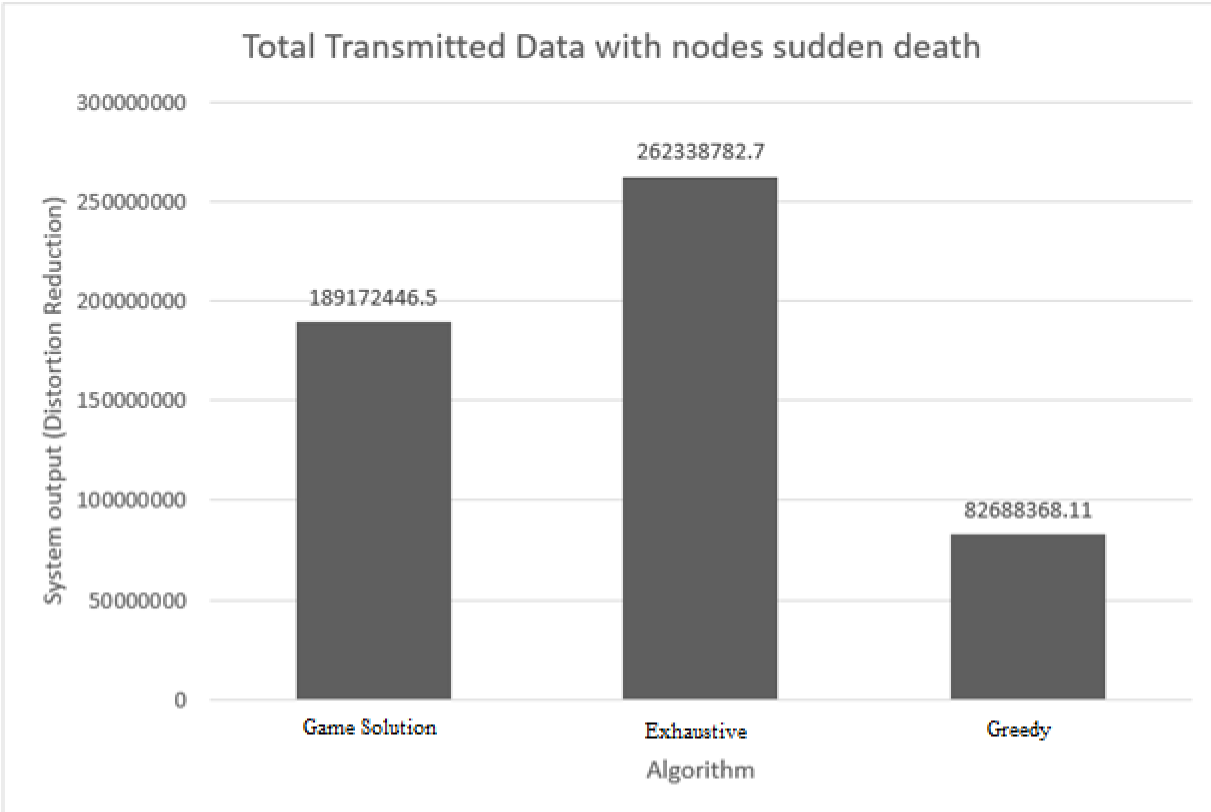

Figure 15. Overall system output of each algorithm in simulation 2

7.3 Different Parameter

In simulation 3, the system starts and runs until nodes are all dead. Only proposed game theory solution will be tested. The main purpose of this simulation is to check the impact of changing parameters.

The parameters for Game Solution are listed in Table 7. The test result is shown in Table 8.

Table 7. Different Parameters

Parameter	Test Case 1	Test Case 2	Test Case 3	Test Case 4
Level Test Ratio	15%	5%	15%	50%
Demotion Threshold	10	10	30	10

Promotion Threshold	10	10	30	10

Table 8. Test result of Simulation 3

	Total DR	Sum of error	Cycle till stable
Test Case 1	206065235	91765399	240
Test Case 2	197312546	87960442	770
Test Case 3	207794729	81310183	500
Test Case 4	166187931	122079738	180

According to the test result, higher level test ratio will make system reach stable state faster, but it will reduce the performance if the test ratio is too high. Low thresholds will also provide a quick stable reach, but it will reduce the stability of the optimized result.

8. CONCLUSION

The growing wireless network performance requirement and increasing mobile device density makes a big problem on wireless network management. To solve the problem, a distributed network management has been considered as a reasonable way. By applying game theory into wireless network pairing system, a distributed self-organized wireless system is built up. The simulation result shows the proposed algorithm provides a better transmit quality than traditional routing algorithm. However, this game theory algorithm is still not acceptable when system structure changes.

The simulation result also points out that changing parameters used in this algorithm would affect the performance. During the simulation test, parameters are found to need be justified based on the system detail. How to setup the parameters depending on an existing application would be an interesting topic for further study.

Since game theory is based on competition and cooperation with incomplete information, there are many solutions can be built based on this theory. As simulation shows, although the proposed algorithm is not perfect, there is huge improvement in performance under an acceptable optimization speed.

LITERATURE CITED

1. B. Suh, C. Won, S.W. Kim, “Minimizing sleep duration time for energy harvesting wireless sensor networks,” in *Proc. IEEE Sensors,* pp.555-559, Oct. 2009
2. A. Kansal, J. Hsu, M. Srivastava, V. Raqhunathan, “Harvesting aware power management for sensor networks,” in *Proc. ACM/IEEE Design Automation Conference.,* pp.651-656, Jul. 2006
3. R. Yao, W. Wang, K. Sohraby. S. Jin, S. Lim, H. Zhu, “A Weight-Optimized Source Rate Optimization Approach in Energy Harvesting Wireless Sensor Networks,” in *Proc. IEEE Globe Com.,* Dec 2012
4. V. Raghunathan, S. Ganeriwal, M. Srivastava, “Emerging techniques for long lived wireless sensor networks," *IEEE Commun. Mag.,* vol. 44, no. 4, pp.108- 114, Apr. 2006
5. V. Raghunathan, P.H. Chou, “Design and power management of energy harvesting embedded systems,” in *Proc. International Symposium on Low Power Electronics and Design,* pp.369-374, Oct. 2006
6. V.C. Gungor, G.P. Hancke, “Industrial wireless sensor networks: challenges, design principles, and technical approaches,” *IEEE Trans. Ind. Electron,* vol. 56, no. 10, pp.4258-4265, Oct. 2009
7. I.F. Akyildiz, T. Melodia, K.R. Chowdury, “Wireless multimedia sensor networks: a survey,” *IEEE Wireless Commun.,*vol. 14, no. 6, pp.32-39, Dec. 2007
8. V. Raghunathan, C. Schurgers, P. Sung, M.B. Srivastava, “Energy-aware wireless microsensor networks,” *IEEE Signal Process. Mag.,* vol. 19, no. 2, pp.40-50, Mar. 2002

9. J. Huang, H. Wang, Y. Qian, C. Wang, “Priority-based Traffic Scheduling and Utility Optimization for Cognitive Radio Communication Infrastructure-based Smart Grid,” *IEEE Trans. Smart Grid,* vol.4, no.1, pp.78-86, March 2013

10. J. Huang, H. Wang, Y. Qian, C. Wang, “Smart grid communications in challenging environments,” in *Proc. IEEE Third International Conference on Smart Grid Communications (SmartGridComm),* pp.552-557,Nov. 2012

11. W. Wang, H. Wang, K. Hua, S. Wu, F. Gao, X. Liao, T. Jiang, “Quality-Optimized Energy Neutrality with Link Layer Resource Allocation for Zero-Power Harvesting Wireless Communications,” in *Proc. IEEE Global Communications Conference (GLOBECOM),* 5pp, Dec. 2011.

12. Niyato, D.; Hossain, E., "Radio resource management games in wireless networks: an approach to bandwidth allocation and admission control for polling service in IEEE 802.16 [Radio Resource Management and Protocol Engineering for IEEE 802.16]," *Wireless Communications, IEEE,* vol.14, no.1, pp.27,35, Feb. 2007

13. Xiangwu Wang; Yanbo Zhang; Lei Zhang; Xinli Mei, "Grasping money game used in wireless channel resource allocation," *Computer Science and Network Technology (ICCSNT), 2012 2nd International Conference,* pp.617,620, 29-31 Dec. 2012

14. J. Hsu, S. Zahedi, A. Kansal, M. Srivastava, V. Raghunathan, “Adaptive duty cycling for energy harvesting systems,” in *Proc. International Symposium on Low Power Electronics and Design*, pp.180-185, Oct. 2006

15. J. Polastre and D. Culler, “Versatile Low Power Media Access for Wireless Sensor Networks,” *ACM Conf. Embedded Networked Sensor Sys.*, 2004, pp. 95–107.

16. C. Schurgers et al.“Optimizing Sensor Networks in the Energy-Latency-Density Design Space,” *IEEE Trans. Mobile Comp.*, vol. 1, no. 1, Jan. 2002, pp. 70–80.
17. C. Enz et al. “WiseNET: An Ultra Low Power Wireless Sensor Network Solution,” *IEEE Comp.*, vol. 37, no. 8, Aug. 2004, pp. 62–70.
18. W. Ye, J. Heidemann, and D. Estrin, “An Energy-Efficient MAC Protocol for Wireless Sensor Networks,” *IEEE INFOCOM’02*, pp. 1567–76.
19. S. Ganeriwal et al.“Estimating Clock Uncertainty for Efficient Duty-Cycling in Sensor Networks,” *ACM Conf. Embedded Networked Sensor Sys.*, 2005, pp. 130–41.
20. B. Schott eet al.“A Modular Power-Aware Micro Sensor with >1000X Dynamic Power Range,” *IEEE Int’l. Symp. Info. Process. Sensor Net.*, 2005, pp. 469–74
21. S. Vural, Y. Tian, and E. Ekici,” QoS-Based Communication Protocols in Sensor Networks,” A. Boukerche, *Algorithms and Protocols for Wireless Ad Hoc and Sensor Networks,* Wiley, 2006.
22. L. Yang and G. B. Giannakis, “Ultra-WideBand Communications: An Idea Whose Time Has Come,” *IEEE Sig. Processing,* vol. 21, no. 6, Nov. 2004, pp. 26–54.
23. M. C. Vuran and I. F. Akyildiz, “Cross-Layer Analysis of Error Control in Wireless Sensor Networks,” *Proc. IEEE Intl. Conf. on Sensor and Ad Hoc Commun. and Networks,* Reston, VA, Sept. 2006
24. V. Tsiatsis, S. Zimbeck, and M. Srivastava, “Architectural strategies for energy efficient packet forwarding in wireless sensor networks,” *in Proc. ISLPED,* 2001, pp. 92-95.

25. A. Wang, S-H. Cho, C.G. Sodini, and A.P. Chandrakasan, "Energy-efficient modulation and MAC for asymmetric micro sensor systems," in *Proc. ISLPED*, 2001, pp 106-111.

26. C. Schurgers, O. Aberthorne, and M. Srivastava, "Modulation scaling for energy aware communication systems," in *Proc. ISLPED*, 2001, pp. 96-99

27. D. Estrin and R. Govindan, "Next century challenges: Scalable coordination in sensor networks," in *Proc. Mobicom*, 1999, pp. 263-270.

28. W. Heinzelman, A. Chandrakasan, and H. Balakrishnan, "Energy-efficient communication protocol for wireless sensor networks," in *Proc. Hawaii Intl.Conf. System Sciences*, Hawaii, 2000, pp. 3005-3014.

29. J.-H. Chang and L. Tassiulas, "Energy conserving routing in wireless ad-hoc networks," in *Proc. INFOCOM*, 2000, pp. 22-31.

30. C. Schurgers and M. Srivastava, "Energy efficient routing in sensor networks," in *Proc. Milcom*, 2001.