PERFORMANCE ANALYSIS OF ENERGY EFFICIENT CROSS LAYER APPROACH IN WSN & GOODPUT ANALYSIS IN TWO WAY RELAY NETWORK

A thesis submitted in partial fulfillment of the requirement for the Degree of

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UNDER THE SUPERVISION OF

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ISLAMIC UNIVERSITY OF TECHNOLOGY

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DECLARETION OF THE CANDIDATES

We hereby declare that the thesis entitled "Performance analysis of energy efficient cross layer approach in WSN &goodput analysis in two way relay network (TWRN)" is an authentic record of our study carried out as the requirement for the award of degree of Bachelor of Science in Electrical and Electronic Engineering under the supervision of the ***Prof. Dr. Md. Rakibul Islam,****Professor of the Department of Electrical and Electronic Engineering (EEE), Islamic University of Technology, Dhaka, Bangladesh during January 2014 to November 2014.The matter embodied in this report has not been submitted in part or full to any other university or institute for the award of any other degree.*

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Survivability is one of the critical issues and the most important research topics in the fields of wireless sensor networks (WSNs). Energy efficiency is one of the determining factors for survivability and lifetime of WSNs. In the WSNs, severe energy issue necessitates energy-efficient approach to fulfill application objectives.In this paper, we studied an Energy Optimization Approach based on Cross-Layer for Wireless Sensor Networks named as EOA, which consider the joint optimal design of the physical, medium access control (MAC), and routing layer. The focus of EOA is on the computation of optimal transmission power, routing, and duty-cycle schedule that optimize the WSNs energy-efficiency.

Further we did the goodput analysis in Two-Way Wireless Relay network where two source nodes exchange their information via a relay node indirectly in Rayleigh fading channels. Both Amplify-and-Forward (AF) and Decode-and-Forward (DF) techniques have been analyzed in the TWRN employing a Markov chain model through which the network operation is described and investigated in depth. Automatic Repeat-reQuest (ARQ) retransmission has been applied to guarantee the successful packet delivery. The bit energy consumption and goodput expressions have been derived as functions of transmission rate in a given AF or DF TWRN. Numerical results are used to identify the optimal transmission rates where the bit energy consumption is minimized or the goodput is maximized.

$\boldsymbol{\beta}$	,	***Gaussian noise factor***
$\boldsymbol{k}$	,	***Normalized distance factor***
$\boldsymbol{\alpha}$	,	***Path loss coefficient***
$\boldsymbol{E_b}$	,	***Average bit energy consumption***
$\boldsymbol{K_i}$	,	***Number of transmission round corresponding to state S***
$\boldsymbol{B}$	,	***Channel bandwidth***
$\boldsymbol{\sigma_n}$	,	***Power spectrum density of the Gaussian white noise***

CHAPTER 2: ENERGY OPTIMIZATIONCROSS LAYER APPROACH

CHAPTER 3:TWO-WAY WIRELESS RELAY NETWORK

CHAPTER 1

INTRODUCTION TO WIRELESS SENSOR NETWORK

A wireless sensor network (WSN) of spatially distributed autonomoussensors to *monitor* physical or environmental conditions, such as temperature, sound, pressure, etc. and to cooperatively pass their data through the network to a main location. The more modern networks are bi-directional, also enabling *control* of sensor activity. The development of wireless sensor networks was motivated by military applications such as battlefield surveillance; today such networks are used in many industrial and consumer applications, such as industrial process monitoring and control, machine health monitoring, and so on.

The WSN is built of "nodes" – from a few to several hundreds or even thousands, where each node is connected to one (or sometimes several) sensors. Each such sensor network node has typically several parts: a radio transceiver with an internal antenna or connection to an external antenna, a microcontroller, an electronic circuit for interfacing with the sensors and an energy source, usually a battery or an embedded form of energy harvesting. A sensor node might vary in size from that of a shoebox down to the size of a grain of dust, although functioning "motes" of genuine microscopic dimensions have yet to be created. The cost of sensor nodes is similarly variable, ranging from a few to hundreds of dollars, depending on the complexity of the individual sensor nodes. Size and cost constraints on sensor nodes result in corresponding constraints on resources such as energy, memory, computational speed and communications bandwidth. The topology of the WSNs can vary from a simple star network to an advanced multi-hop wireless mesh network. The propagation technique between the hops of the network can be routing or flooding.

In computer science and telecommunications, wireless sensor networks are an active research area with numerous workshops and conferences arranged each year, for example IPSN, SenSys, and EWSN.

1.1 Applications

Process Management

Area monitoring is a common application of WSNs. In area monitoring, the WSN is deployed over a region where some phenomenon is to be monitored. A military example is the use of sensors detect enemy intrusion; a civilian example is the geo-fencing of gas or oil pipelines. Area monitoring is most important part.

Health care monitoring

The medical applications can be of two types: wearable and implanted. Wearable devices are used on the body surface of a human or just at close proximity of the user. The implantable medical devices are those that are inserted inside human body. There are many other applications too e.g. body position measurement and location of the person, overall monitoring of ill patients in hospitals and at homes. Body-area networks can collect information about an individual's health, fitness, and energy expenditure.[3]

Environmental/Earth sensing

There are many applications in monitoring environmental parameters, examples of which are given below. They share the extra challenges of harsh environments and reduced power supply.

Air pollution monitoring

Wireless sensor networks have been deployed in several cities (Stockholm, London and Brisbane) to monitor the concentration of dangerous gases for citizens. These can take advantage of the ad hoc wireless links rather than wired installations, which also make them more mobile for testing readings in different areas.

Forest fire detection

A network of Sensor Nodes can be installed in a forest to detect when a fire has started. The nodes can be equipped with sensors to measure temperature, humidity and gases which are produced by fire in the trees or vegetation. The early detection is crucial for a successful action of the firefighters; thanks to Wireless Sensor Networks, the fire brigade will be able to know when a fire is started and how it is spreading.

Landslide detection

A landslide detection system makes use of a wireless sensor network to detect the slight movements of soil and changes in various parameters that may occur before or during a landslide. Through the data gathered it may be possible to know the occurrence of landslides long before it actually happens.

Water quality monitoring

Water quality monitoring involves analyzing water properties in dams, rivers, lakes & oceans, as well as underground water reserves. The use of many wireless distributed sensors enables the creation of a more accurate map of the water status, and allows the permanent deployment of monitoring stations in locations of difficult access, without the need of manual data retrieval.[4]

Natural disaster prevention

Wireless sensor networks can effectively act to prevent the consequences of natural disasters, like floods. Wireless nodes have successfully been deployed in rivers where changes of the water levels have to be monitored in real time.

Machine health monitoring

Wireless sensor networks have been developed for machinery condition-based maintenance (CBM) as they offer significant cost savings and enable new functionality.[5] In wired systems, the installation of enough sensors is often limited by the cost of wiring. Previously inaccessible locations, rotating machinery, hazardous or restricted areas, and mobile assets can now be reached with wireless sensors.

Data logging

Wireless sensor networks are also used for the collection of data for monitoring of environmental information, this can be as simple as the monitoring of the temperature in a fridge to the level of water in overflow tanks in nuclear power plants. The statistical information can then be used to show how systems have been working. The advantage of WSNs over conventional loggers is the "live" data feed that is possible.

Water/Waste water monitoring

Monitoring the quality and level of water includes many activities such as checking the quality of underground or surface water and ensuring a country's water infrastructure for the benefit of both human and animal.It may be used to protect the wastage of water.

Structural Health Monitoring

Wireless sensor networks can be used to monitor the condition of civil infrastructure and related geo-physical processes close to real time, and over long periods through data logging, using appropriately interfaced sensors.

1.2 Characteristics

The main characteristics of a WSN include:

- Power consumption constraints for nodes using batteries or energy harvesting
- Ability to cope with node failures (resilience)
- Mobility of nodes
- Heterogeneity of nodes

- Scalability to large scale of deployment
- Ability to withstand harsh environmental conditions
- Ease of use
- Cross-layer design

Cross-layer is becoming an important studying area for wireless communications. In addition, the traditional layered approach presents three main problems:

1. Traditional layered approach cannot share different information among different layers , which leads to each layer not having complete information. The traditional layered approach cannot guarantee the optimization of the entire network.
2. The traditional layered approach does not have the ability to adapt to the environmental change.
3. Because of the interference between the different users, access confliction, fading, and the change of environment in the wireless sensor networks, traditional layered approach for wired networks is not applicable to wireless networks.

So the cross-layer can be used to make the optimal modulation to improve the transmission performance, such as data rate, energy efficiency, QoS (Quality of Service), etc.. Sensor nodes can be imagined as small computers which are extremely basic in terms of their interfaces and their components. They usually consist of a *processing unit* with limited computational power and limited memory, *sensors* or MEMS (including specific conditioning circuitry), a *communication device* (usually radio transceivers or alternatively optical), and a power source usually in the form of a battery. Other possible inclusions are energy harvesting modules,[6] secondary ASICs, and possibly secondary communication interface.

The base stations are one or more components of the WSN with much more computational, energy and communication resources. They act as a gateway between sensor nodes and the end user as they typically forward data from the WSN on to a server. Other special components in routing based networks are routers, designed to compute, calculate and distribute the routing tables.

1.3 Platforms

1.3.1 Hardware

One major challenge in a WSN is to produce *low cost* and *tiny* sensor nodes. There are an increasing number of small companies producing WSN hardware and the commercial situation can be compared to home computing in the 1970s. Many of the nodes are still in the research and development stage, particularly their software. Also inherent to sensor network adoption is the use of very low power methods for radio communication and data acquisition.

In many applications, a WSN communicates with a Local Area Network or Wide Area Network through a gateway. The Gateway acts as a bridge between the WSN and the other network. This enables data to be stored and processed by devices with more resources, for example, in a remotely located server.

1.3.2 Software

Energy is the scarcest resource of WSN nodes, and it determines the lifetime of WSNs. WSNs may be deployed in large numbers in various environments, including remote and hostile regions, where ad hoc communications are a key component. For this reason, algorithms and protocols need to address the following issues:

- Lifetime maximization
- Robustness and fault tolerance
- Self-configuration

Lifetime maximization: Energy/Power Consumption of the sensing device should be minimized and sensor nodes should be energy efficient since their limited energy resource determines their lifetime. To conserve power the nodes normally turn off the radio transceiver when not in use.

Some of the important topics in WSN(Wireless Sensor Networks) software research are:

- Operating systems
- Security
- Mobility
- Usability
- Maintenance

1.4 Operating systems

Operating systems for wireless sensor network nodes are typically less complex than general-purpose operating systems. They more strongly resemble embedded systems, for two reasons. First, wireless sensor networks are typically deployed with a particular application in mind, rather than as a general platform. Second, a need for low costs and low power leads most wireless sensor nodes to have low-power microcontrollers ensuring that mechanisms such as virtual memory are either unnecessary or too expensive to implement.

It is therefore possible to use embedded operating systems such as eCos or uC/OS for sensor networks. However, such operating systems are often designed with real-time properties.

TinyOS is perhaps the first operating system specifically designed for wireless sensor networks. TinyOS is based on an event-driven programming model instead of multithreading. TinyOS programs are composed of *event handlers* and *tasks* with run-to-completion semantics. When an external event occurs, such as an incoming data packet or a sensor reading, TinyOS signals the appropriate event handler to handle the event. Event handlers can post tasks that are scheduled by the TinyOS kernel some time later.

LiteOS is a newly developed OS for wireless sensor networks, which provides UNIX-like abstraction and support for the C programming language.

Contiki is an OS which uses a simpler programming style in C while providing advances such as 6LoWPAN and Protothreads.

RIOT implements a microkernel architecture. It provides multithreading with standard API and allows for development in C/C++. RIOT supports common IoT protocols such as 6LoWPAN, IPv6, RPL, TCP, and UDP.

ERIKA Enterprise is an open-source and royalty-free OSEK/VDX Kernel offering BCC1, BCC2, ECC1, ECC2, multicore, memory protection and kernel fixed priority adopting C programming language.

1.5 Online collaborative sensor data management platforms

Online collaborative sensor data management platforms are on-line database services that allow sensor owners to register and connect their devices to feed data into an online database for storage and also allow developers to connect to the database and build their own applications based on that data. Examples include Xively and the Wikisensing platform. Such platforms simplify online collaboration between users over diverse data sets ranging from energy and environment data to that collected from transport services. Other services include allowing developers to embed real-time graphs & widgets in websites; analyse and process historical data pulled from the data feeds; send real-time alerts from any datastream to control scripts, devices and environments.

The architecture of the Wikisensing system is described in describes the key components of such systems to include APIs and interfaces for online collaborators, a middleware containing the business logic needed for the sensor data management and processing and a storage model suitable for the efficient storage and retrieval of large volumes of data.

1.6 Simulation of WSNs

At present, agent-based modeling and simulation is the only paradigm which allows the simulation of complex behavior in the environments of wireless sensors (such as flocking). Agent-based simulation of wireless sensor and ad hoc networks is a relatively new paradigm. Agent-based modelling was originally based on social simulation.

Network simulators like OPNET, OMNeT++, NetSim, WSNet and NS2 can be used to simulate a wireless sensor network.

1.7 Distributed sensor network

If a centralised architecture is used in a sensor network and the central node fails, then the entire network will collapse, however the reliability of the sensor network can be increased by using a distributed control architecture. Distributed control is used in WSNs for the following reasons:

1. Sensor nodes are prone to failure,
2. For better collection of data
3. To provide nodes with backup in case of failure of the central node

There is also no centralised body to allocate the resources and they have to be self organised.

1.8 Data integration and Sensor Web

The data gathered from wireless sensor networks is usually saved in the form of numerical data in a central base station. Additionally, the Open Geospatial Consortium (OGC) is specifying standards for interoperability interfaces and metadata encodings that enable real time integration of heterogeneous sensor webs into the Internet, allowing any individual to monitor or control Wireless Sensor Networks through a Web Browser.

1.9 In-network processing

To reduce communication costs some algorithms remove or reduce nodes' redundant sensor information and avoid forwarding data that is of no use. As nodes can inspect the data they forward, they can measure averages or directionality for example of readings from other nodes. For example, in sensing and monitoring applications, it is generally the case that neighboring sensor nodes monitoring an environmental feature typically register similar values. This kind of data redundancy due to the spatial correlation between sensor observations inspires techniques for in-network data aggregation and mining.

There are several applications that use the Wireless sensor networks (WSNs).Some of them are habitat monitoring, border surveillance and structural monitoring. In most applications, WSNs are required to be operating in order to months to years but constituent sensor nodes have limited battery power. So survivability becomes one of the critical issues in this field of wireless sensor network (WSNs). So the key factors for survivability and lifetime of WSNs is energy efficiency.

There must be some energy waste during operation. Some of them are-

I. Idle listening.
II. Retransmission resulting from collision.
III. Unnecessarily high transmission power.
IV. Sub-optimal utilization of the available resource.

Corresponding to these problems, there is a significant body of approaches to addressing different aspects of energy waste. To mitigate this energy consumption of idle listening, duty cycling mechanisms have been introduces in sensor network MAC protocol. For example, S-MAC[1], SCP-MAC[6] and so on. In[3, 4], some approaches control the transmission power in order to reduce the unnecessary transmission energy consumption and decrease the interference among nodes while maintaining network connectivity.

Power aware routing protocols [7, 8] save significant energy by choosing the appropriate route according to the available energy of nodes or energy demand of transmission paths.

2.1 Cross-Layer Energy Optimization Approach

A cross-layer energy optimization approach named as EOA, which minimizes the aggregate energy consumption in all power states. EOA provides a cross-layer approach that integrates these approaches as a joint optimization problem.

2.1.1 Physical layer

At the physical layer, a feed-back transmission power control algorithm is presented that obtains the minimum transmission power level between each node and its neighboring nodes aiming to reduce power consumption and decrease the interference between two nodes.

In the meanwhile, when the spatial and temporal factors change, this algorithm could adjust the minimum transmission power level dynamically to maintain the good link quality over time. A neighbor table ismaintained at each node. The neighbor table contains the minimum transmission power level that this node should use for its neighbor nodes.

2.1.2 Network layer

At the network layer, an online algorithm called Incremental short-path Tree Heuristic (ISTH) [9] and nodes' neighbor tables is utilized to design a routing algorithm that is different from conventional routing algorithms. In this algorithm, energy consumption between two node in all state (e.g. transmit, receive, idle, sleep) regarded as a metric, and choose the route with the least energy consumption to the sink node to forward packets.

2.1.3 Mac layer

The cross-layer routing information is used to form the sleep/listen scheduling scheme for each sensor node at MAC layer. By this scheme, a node must be awake if and only if it takes part in the actual transmission activity; otherwise it continues to keep asleep in the rest of time. As a result, the idleJOURNAL OF COMMUNICATIONS, VOL. 3, NO. 6, NOVEMBER 2008 27 © 2008 ACADEMY PUBLISHER listening duration of the node decreases and the energy consumption further reduces.

2.2 Classification of the approaches

The cross layer approaches that have been studied here can be classified into three approaches.

2.2.1Interaction of MAC and Physical Layer:

The energy consumption for physical and MAC layer is analyzed in [2], the conclusion is that single-hop communication can be more efficient if real radio model are used. However, the analysis is based on a linear networks, the conclusion may not be practical in realistic scenarios. In [5], a cross-layer solution among MAC layer, physical phenomenon, and the application layer for WSNs is proposed. The spatial correlation in the observed physical phenomenon is exploited for medium access control. Based on a theoretical framework, a distributed, spatial correlation-based collaborative medium access control (CC-MAC) protocol is proposed.

2.2.2 Interaction of MAC and routing Layer:

In many work, the receiver-based routing is exploited for MAC and routing cross-layer modularity. In this approach, the next hop is chosen as a result of contention in the neighborhood. Receiver-based routing has been independently proposed in [13], [14], and [15]. In [14] and [15], the authors discuss the energy efficiency, latency, and multihop performance of the algorithm. In [16], the work in [14] and [15] is extended for a single radio node. In [13], the receiver-based routing is also analyzed based on a simple channel model and lossless links. Moreover, the latency performance of protocol is presented based on different delay function and collision rates. Similarly in [17], the routing decision is performed as a result of successive competitions at the medium access level. More specifically, the next hop is selected based on a weighted progress factor and the transmit power is increased successively until the most efficient node is found. Moreover, on-off scheduled are used. The performance evaluations of all these propositions present the advantages of cross-layer approach at the routing and MAC layer. The usage of on-off schedules in a cross-layer routing and MAC framework is also investigated in [20]. In this work, a TDMA-based MAC scheme is devised, where nodes distributively select their appropriate time slots based onlocal topology information. The routing protocol also exploits this information for route establishment.

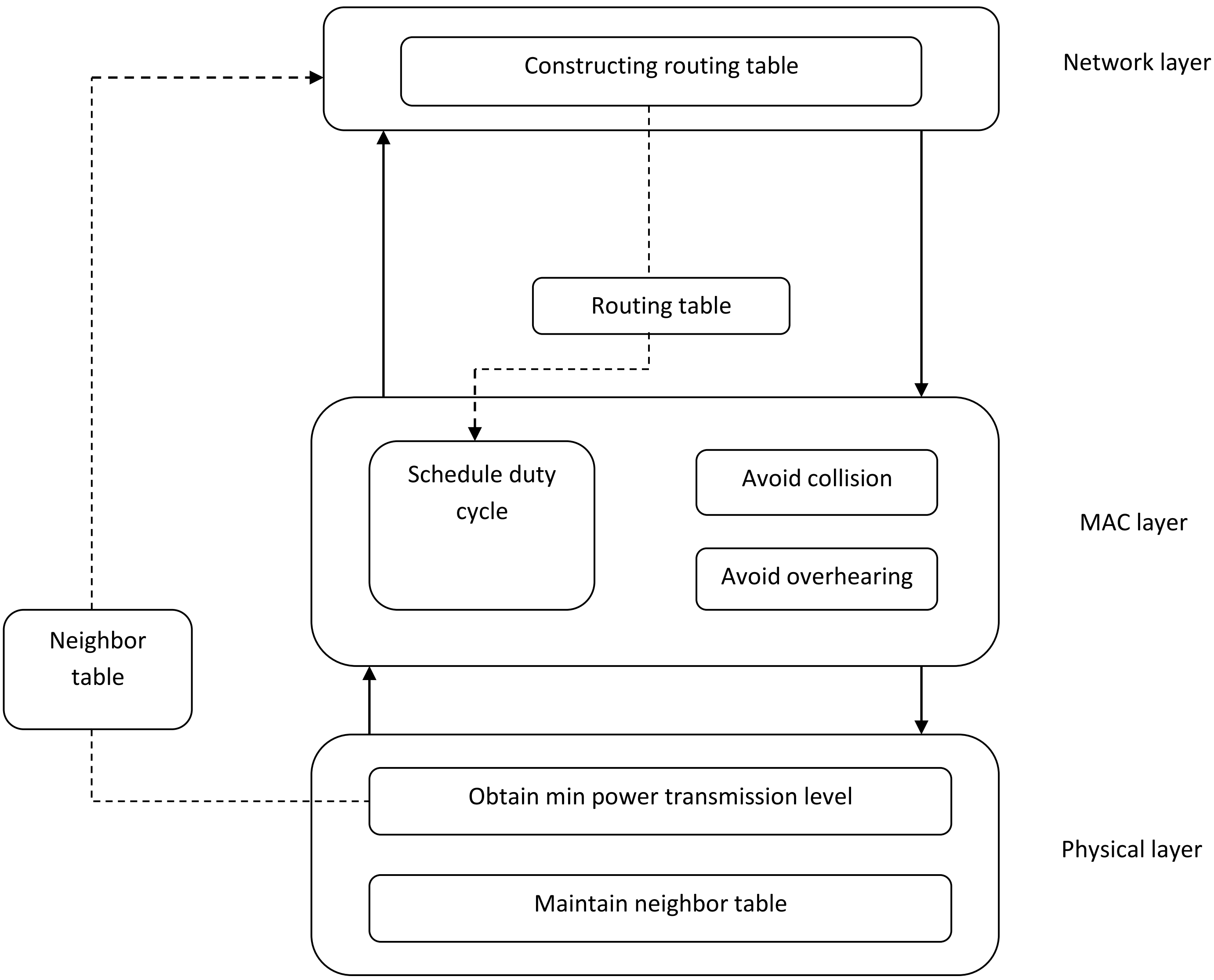

Figure 2.1: The frame of Energy optimization approach

2.2.3 Interaction of Physical, Mac and Routing Layer:

In addition to the proposed methods that focus on pair wise cross-layer interaction, more general cross-layer approaches among three protocol layer exist. In [18], the optimization of transmission power, transmission rate, and link schedule for TDMA-based WSNs is proposed. The optimization is performed to maximize the network lifetime, instead of minimizing the total average power consumption. In [19], joint routing, MAC, and link layer optimization is proposed. The authors consider a variable-length TDMA scheme and MQAM modulation. The optimization problem considers energy consumption that includes both transmission energy and circuit processing energy. Based on this analysis, it is shown that single-hop communication may be optimal in some cases where the circuit energy dominates the energy consumption instead of transmission energy.

2.4 Energy optimization

Cross-layer approach mentioned in this paper considers the interaction between corresponding protocol layers, and preserves the traditional layered structure. Each layer is informed about the conditions of other layers, while the mechanisms of each layer still stay intact. Guided by above cross-layer principle, a cross-layer optimization approach is designed named as EOA. Fig.2.1 shows the frame of EOA. In the physical layer, EOA controls transmission power dynamically and obtains the proper transmission power level between two nodes. In the meanwhile, each node maintains a neighbor table to record this proper transmission power level. Then each node in the network layer constructs its routing table by utilizing the neighbor table of the physical layer. Finally, EOA uses the cross-layer routing information to determine the duty-cycle of each node, and meanwhile EOA also pays attentions to collision and overhearing problem in the MAC layer.

2.5 Transmission Power Control Algorithm:

The transmission power between two nodes is affected by two factors-

1. Spatial factor
2. Temporal factor

2.5.1 Spatial factor

The spatial factors include the surrounding environment, such as terrain and the distance between the transmitter and the receiver.

2.5.2 Temporal factor

Temporal factors include surrounding environmental changes in general, such as weather conditions.

This phenomenon indicates the previous topology control solutions, which use static transmission power, lead to worse link quality and unnecessarily high energy consumption. As a result, the transmission power of each node needs to be set the right level dynamically with spatial and temporal change.

2.6 Dynamic transmission power control algorithm

ATPC [10] reveals that radio CC1000 [11] and CC2420 [12] offers a Received Signal Strength Indicator (RSSI) to specify the transmission power level during runtime, such that system design is able to dynamically control the transmission power. Therefore, we present a dynamic transmission power control algorithm based on RSSI, which contains two phases-

1. Initialization phase
2. Running tuning phase

2.6.1 Initialization phase

At the initialization phase, the objective of this algorithm is to make every node in a WSNs find the minimum transmission power level that can communication with its neighboring nodes successfully. At the same time, the neighbor table is maintained at each node. The neighbor table contains the proper transmission power level and the number of neighbor node.

2.6.1.1 Mechanism of initialization phase

Suppose the communications are almost symmetric between the nodes, namely the transmission power is almost equal when the two nodes communicate each other, and set a threshold of RSSI $R_{threshold}$which is the minimum necessary RSSI for the reception of a data packet. Assessing the minimum transmission power level requires three steps (Figure 2.2):

1. Each node broadcasts a beacon message with themaximum transmission power level P_{t_max}.

2. A node *B* that receives the beacon message from node *A* gets the transmission power levelP_r according to the RSSI reading, and uses the Equation(1) to calculate the minimum transmission power level P_{t_min}

$$P_{t\_m} = \frac{P_{t\_max} R_{threshold}}{P_r}$$

Then node *B* sends the ACK message that contains P_{t_m} to node *A.*

3. Node *A* gains the value of P_{t_m} from ACK message of *B* , and record this value and *B* in the neighbor table.

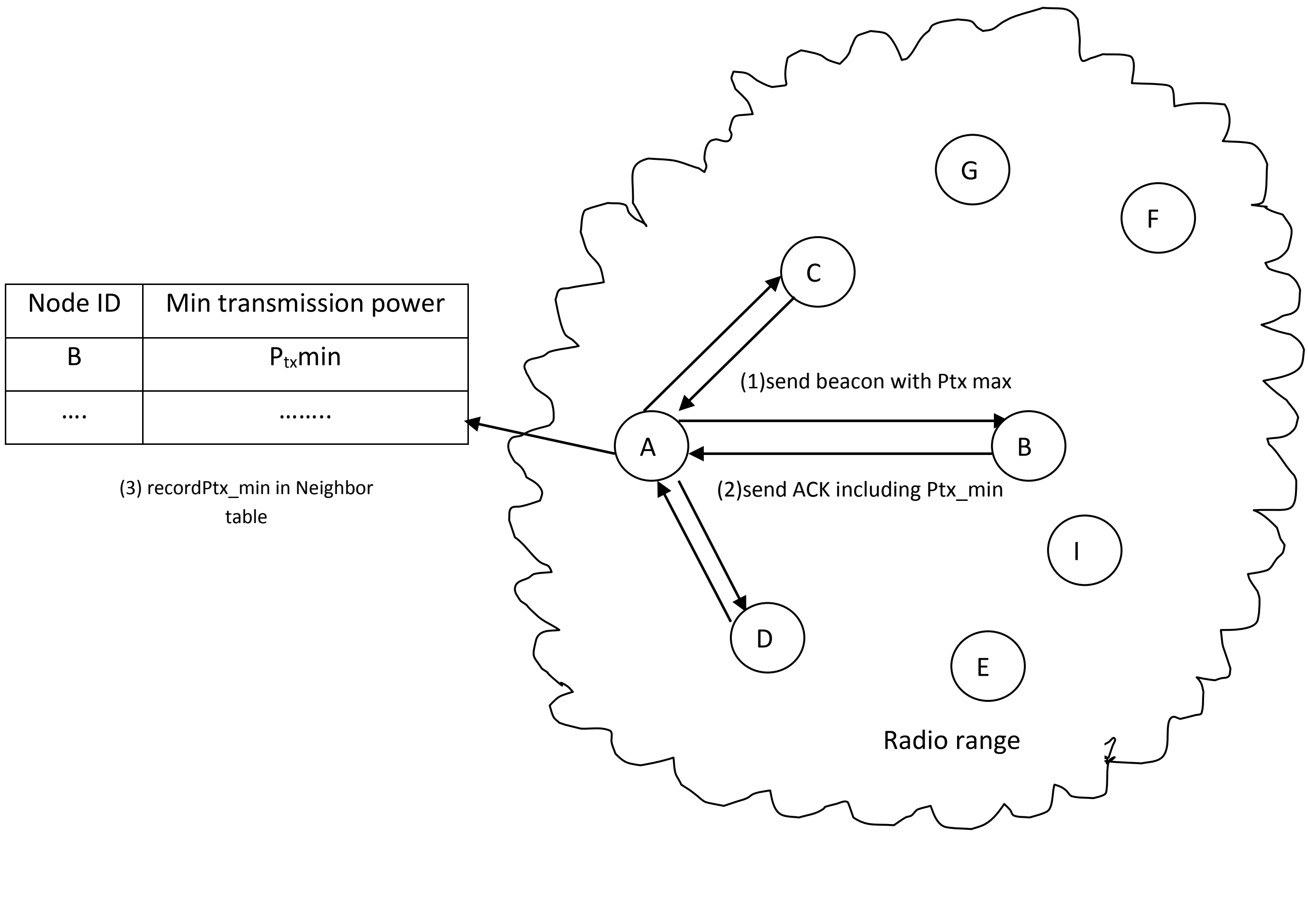

Figure 2.2: Operation of transmission power control

2.6.2 Running tuning phase

At the runtime tuning phase, this algorithms could adjust the proper transmission power dynamically to adapt environmental change.

2.6.2.1 Mechanism of running tuning phase

In the runtime tuning phase, a feedback mechanism is adopted to tune the transmission power level. Figure 2.3 is an overview of the feedback mechanism.

To simplify the description, we show a pair of nodes. When node A has a packet to send to its neighbor B, it first adjusts the transmission power level indicated by its neighbor table in the initialization phase, and then transmission the packets. When node B receives this packet and read RSSI value, then send back ACK message including RSSI value. Node A compares this RSSI with a lower threshold $R_{threshold\_low}$ if the RSSI value is below $R_{threshold\_low}$ Node A increases the transmission power level step by step, and send the packet until the RSSI value is above $R_{threshold\_low}$.

Otherwise, if the RRSI value is above than an upper threshold $R_{threshold\_upp}$, Node A decreases the transmission power level step by step, and send the packet until the RSSI value is below $R_{threshold\_upp}$. $R_{threshold_low}$and $R_{threshold_upp}$are $R_{threshold}- 6$ and + 6 $R_{threshold}$ respectively since the RSSI accuracy of the CC1000 and CC2420 are ± 6 .In this phase, each node precisely determines the minimum transmission power level that provides good link quality and dynamically maintains the transmission power level over time.

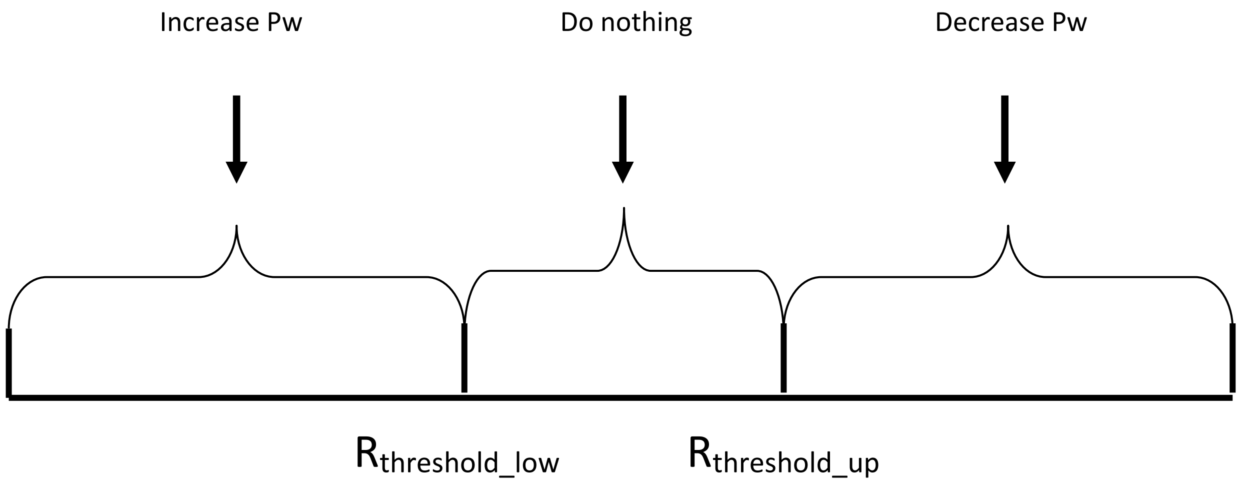

Figure 2.3:Adjusting transmission power level

2.7 Routing Table Construction:

The construction of route using the neighbor table mentioned in previous section. At the route construction step, each sensor node needs to figure out a better way to select its next-hop node. An efficient route for WSNs is expected to be able to

1) Minimize the end-to-end delivery time, i.e. the sensing data could be timely delivered to the sink such that the decision maker can take immediate action to deal with that emergency event.

2) Save more energy consumption via the better routing decision. Therefore, source nodes must find the energy-efficient routing path to the sink node.

2.7.1 Incremental Shortest-path Tree Heuristic (ISTH)

Here, an online algorithm called Incremental Shortest-path Tree Heuristic (ISTH) [9] is described. ISTH algorithm requires that different source nodes share the node of the routing path found as much as possible, which makes the number of nodes in active less, and hence more nodes are in sleep state. Now the basic idea of ISTH is explained; a detailed description can be found in [9].ISTH finds the energy-efficient route to the sink according to the following cost metric:

$$C(u,v) = \begin{cases} \frac{R_i}{B} * \ C_{u,v} + Z \ , \ \ u\ is\ inactive \\ \frac{R_i}{B} * \ C_{u,v} \ \ , \ \ u\ is\ active \end{cases}$$

Wherenode *v* is the next-hop node of *u.*

2.7.2 Total power consumption

From the previous equation, on the path $C(u,v)$ represents the total power consumption between node *u* and node *v* and that is

$$C(u,v) = P_{tx}(u,v) + P_{rx} - 2P_{id}$$

Which is the total power consumption in all modes of node u , where P_{tx}(*u*, *v*) is the P_{t_min} (between node u and node v) mentioned in previous section, P_{rx} , P_{id}represent reception, and idle power consumption respectively, *Z*is the nodal power consumption, $R_i$is the data rate, the bandwidth of all nodes is B. In (2), if node *u* is not on the path from any source nodes to sink node, node *u* is inactive, and *C*(*u*, *v*) not only includes $C_{u,v}$but also includes the power consumption of node u . Otherwise, if node *u* is already on the path from other source nodes to sink node, node *u* is active, and *C*(*u*, *v*) only includes $C_{u,v}$.This is because Z has been counted by the existing routes.

2.8 Constructing a routing table:

The routing table can be constructed based on the ISTH algorithm and the nodes' neighbor table described in previous section. Each node calculates the power consumption with neighbor nodes by (2), and finds an energy-efficient routing path to the sink by ISTH algorithm. During this process, each node sets the neighbor node with the minimum energy consumption to the sink as its next-hop node and constructs a table to record its routing information.

Each node in WSNs maintains a routing table that contains the routing entries and status of neighbors.

Specifically, an entry in the routing table of node *u*includes following fields: *next_hop*, *cost*, *power_level*,*destination*>where *next_hop*is the neighbor node with the minimum cost to the sink, *cost* is the cost of node *u*to the sink through *next_hop*,*power_level*is the power level between node *u* and *next_hop*. *destination*is the routing path's destination node. Table 1 shows a routing table of a node.

2.9 Duty-cycle Scheduling of Nodes

Duty cycle mechanisms have been used in sensor networks to improve energy efficiency. For example SMAC [1], each sensor node follows a periodic synchronized listen/sleep schedule. However, S-MAC introduces nonessential idle-listening, since node must be waken up when its sleep period expires, even when the node is not transmitting or receiving a data packet. This nonessential idle-listening is very inefficient and wasted significant energy.

In the meanwhile, the duty-cycle mechanisms have other limitations. Most importantly, end-to-end delivery latency may be increased substantially; for example, with S-MAC, in each operational cycle, a data packet can be forwarded over a single hop only, since an intermediate relaying node has to wait for its next-hop node to wake up to receive the packet. Motivated by the above problem, we exploit cross-layer routing information to design the duty-cycle scheduling scheme for each sensor node. In this scheme, we exploit the routing information to form the nodes'duty-cycle schedule.

This process contains two stages: synchronization stage and packets' transmitting stage.

2.10 Synchronization Stage

In the synchronization stage, nodes in the same routing path own the same duty-cycle schedule in order to reduce end-to-end delivery latency, So that data packets would be forwarded to sink node rapidly.

Firstly, sink node computes duty-cycle schedules according to known routing information. Then, sink node disseminates computed duty-cycle schedules to every node through the routing paths.

Each node exchanges duty-cycle schedules with all 1-hop neighbors, so that nodes in the same path wake up and sleep at the same time. Specially, if a node belongs with multiple paths, it follows the duty-cycle schedule of source node which has early wake-up

schedule. If a node doesn't belong to any routing paths, its duty-cycle schedule is set to infinity.

Figure 2.4 shows a simple network topology, node E, node F and node A belong to path-1; node A, node B, node C and node D belong to path-2.node E and node F own the same duty-cycle schedule; node B, node C and node D also own the same duty-cycle. And node A not only belongs to the path-1, but also belongs to the path-1, so its schedule depends on source node F and D.

If node F's schedule is earlier than node D's, node A follow the schedule of node F, or it follow the node D. Node G don't any routing paths, then its schedule is set to infinity.

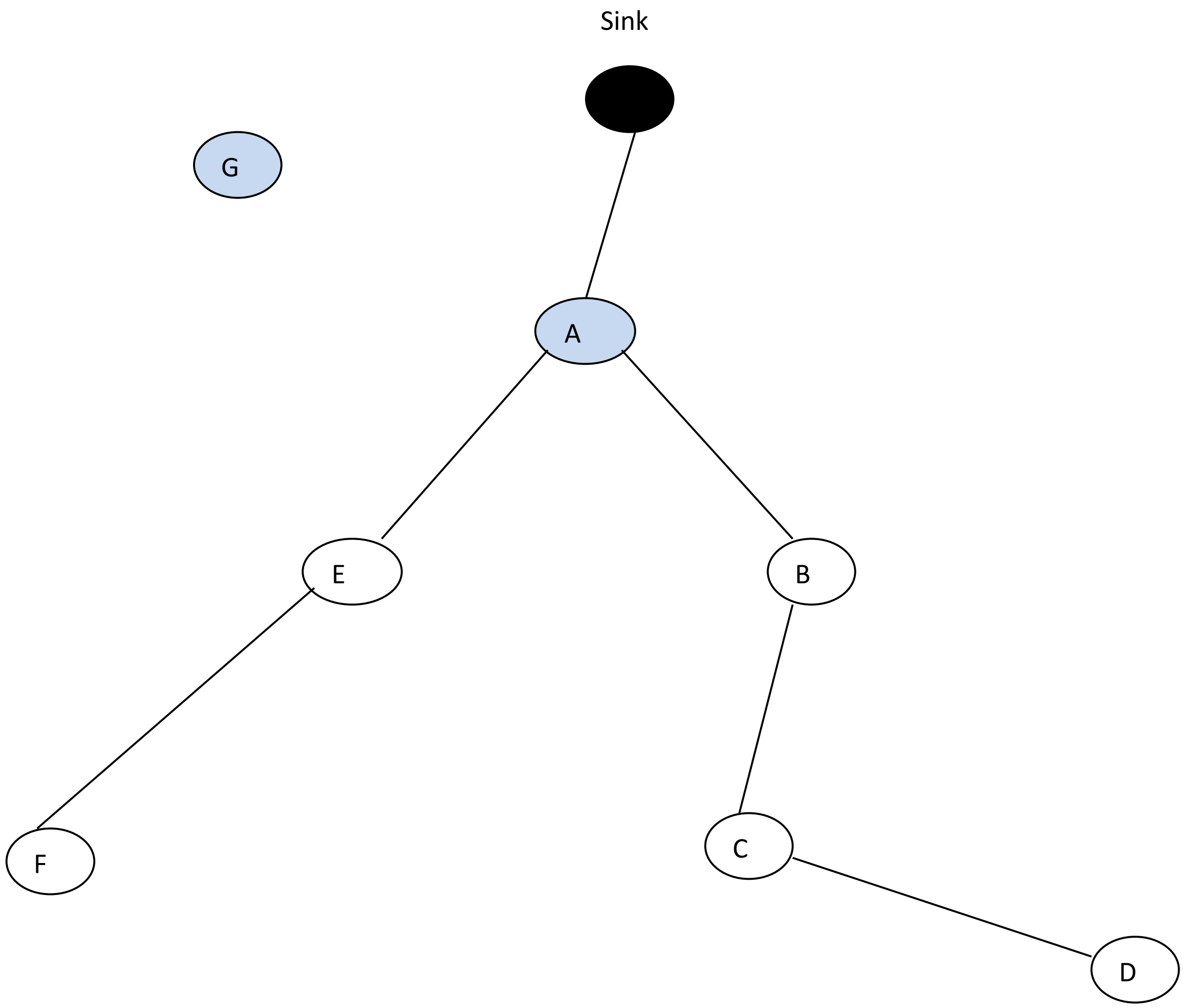

Figure 2.4: A network topology

2.10.1 Modification of routing table

To record each node's schedule, routing tables is modified by introducing a new field. So an entry in the routing table of node *u* becomes following fields: <*next_hop*, *cost*, *power_level*, *destination, schedule*. In the S-MAC protocol, nodes exchange and coordinate on their sleep schedules by periodically broadcasting SYNC frame to all immediate neighbors. We also employ SYNC frame to exchange all nodes' duty-cycle schedule. After sink node computed dutycycle for each path, sink node send SYNC frame to disseminate schedule information, node that receives this SYNC frame record his duty-cycle.

2.10.2 Transmission Stage

Packet transmitting stage contains wake-up stage and transmission stage. When a node has data to send, the node firstly checks whether intermediate nodes are active period in the wake-up stage. In Figure 2.5, source node A has data to send to final destination sink node.

Node A first picks a random period from the contention window and waits for the medium to be quiet for that period and an additional (DIFS) period before sending a wake-up frame to B. If node B is active state, and receives the wake-up frame from node A, then it sends a CTS frame back to node A. After B receives a wake-up frame, unless B is the final destination of this routing path, B gets the next-hop address for this destination from its own routingtable. B then waits a SIFS period before transmitting its own wake-up frame. As in IEEE 802.11, SIFS is long enough for a node to switch its transmitting/receive mode and to do necessary data processing.

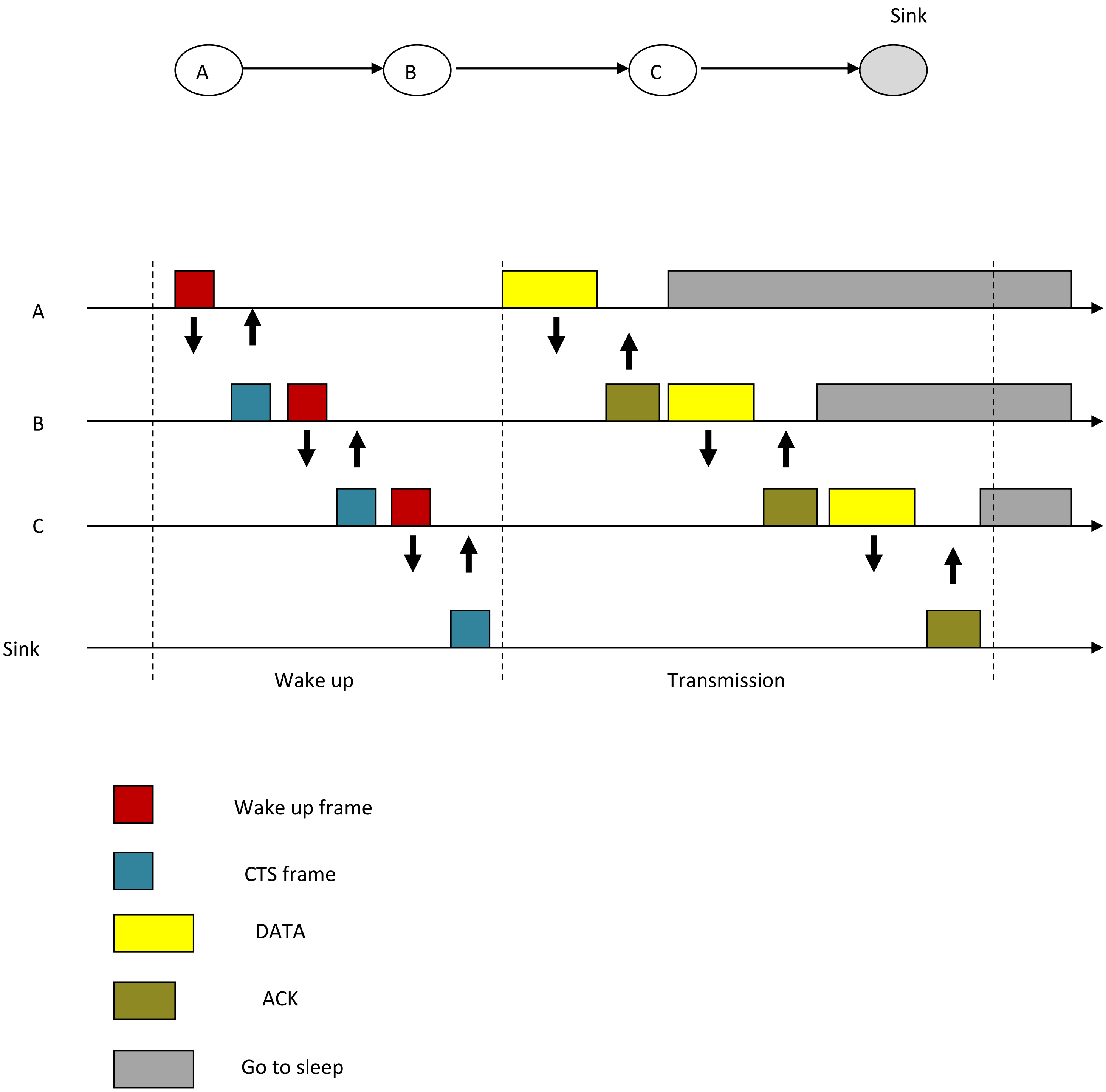

Figure 2.5: The duty-cycle scheduling scheme

Upon receiving B’s wake-up frame, C performs the same steps as A. This process of receiving a CTS and immediately transmitting another wake-up frame continues until either the final destination has received the wake-up frame or the end of the current node’s active period is reached.All data packets are transmitted in the transmission stage.

In the example in Figure 2.5, when the first node A receives the CTS frame, it waits until the start of the transmission stage to transmit the data packets. Node B keeps awake to receive the data packet at the start of the transmission stage, and after node B receives the data packet, it sends and ACK frame to S. After receiving the ACK, node A goes to sleep mode. This data packetsrelaying process continues at each hop until the final destination is reached or the data frame reaches some node that did not receive a CTS from it next hop, in which case the node just hold data frame until the wakeup period of the next operational cycle. This entire process is repeated until the final destination is reached.

2.11 Conclusion:

So an energy optimization approach for wireless sensor networks is present, named EOA which exploits the cross-layer principle that takes into the physical layer (i.e. the transmission power), MAC layer (i.e. the duty-cycle scheduling), and network layer (i.e. the routing protocol) account. EOA is able to use the physical layer’s transmission power as metric to choose the routing path with optimal energy consumption, and use the network layer’s routing information to determine the MAC layer’s duty-cycle. The results of analytical simulation experiment and real platform shows that EOA conserve more energy and leads to the better system performance.

The two-way relay networks (TWRNs) in which two source nodes T_1 and T_2 without a direct link communicate with each other via a relay node. The architecture of TWRNs makes it possible to better exploit the channel multiplexing of uplink and downlink wireless medium.The source nodes initially send their data to the relay node.

3.1 Objectives

Two techniques have been analyzed-

1. Amplify-and-Forward (AF) mode
2. Decode-and-Forward (DF) mode

The received data is combined employing a certain method according to the Amplify-and-Forward (AF)or the Decode-and-Forward (DF) mode and gets broadcasted from the relay back to both source nodes. With the application of network coding and channel estimation techniques [22], T_1 and T_2 can perform self-interference cancelation and remove their own transmitted codewords from the received signal.

Prior works [25], [26] also show there is a compromise between transmission rate R and ARQ such that the network average successful throughput, i.e., the goodput, can be maximized at an optimal rate $R*$. In addition to the goodput analysis, we are interested in energy-efficient operation. In such cases, the energy consumption due to retransmission should also be taken into account to evaluate the energy efficiency with respect to R. Hence, we investigate the joint optimization of R (at the physical layer) and the number of ARQ retransmissions (at the data-link layer) by adopting a cross-layer framework in TWRNs.

3.2 Transmission process

Four time slots needed in a traditional one-way transmission for the forward and backward channels to accomplish one-round information exchange between $T_1$and T_2via the relay node can be reduced to two in TWRNs by comparison. In a realistic multi-user wireless network, e.g. IS-856 system [23] which has more relaxed delay requirements, the transmission power is fixed while the rate can be adapted according to the channel conditions. Moreover, Automatic Repeat request (ARQ) techniques have been applied to improve the transmission reliability above the physical layer [24].

3.3 Overview

Now we divide the analysis in different parts to explain our work. Part 3.4introduces the TWRN model, channel assumptions as well as its general working mechanism. In Part 3.5and 3.6, we investigate the Markov chain model under both AF and DF modes to derive the analytical expressions for the bit energy consumption and goodput. In Part 3.7, the numerical results are shown to compare the system performance in AF and DF modes. Part 3.8 provides the conclusion.

3.4 System formulation and channel assumptions

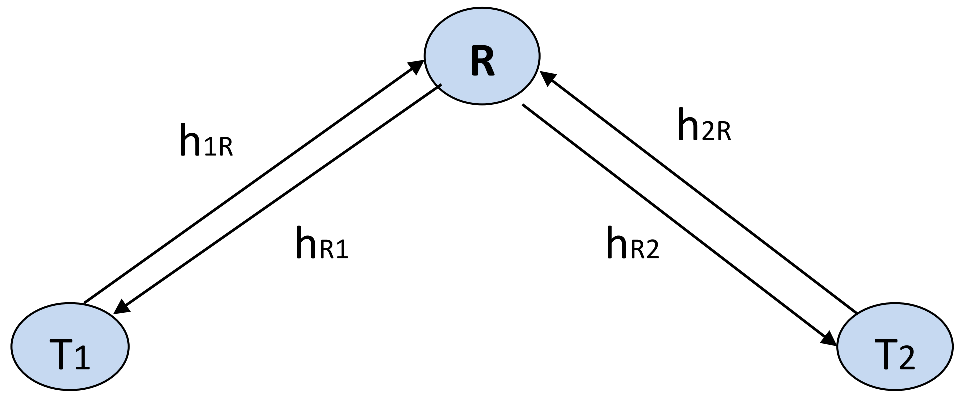

Figure 3.1 : Two-way relay network model

We depict a 3-node TWRN where source nodes T_1 and T_2 can only exchange information via the relay node. Codewords x_1 and x_2 from T_1 and T_2, respectively, have equal length and unit energy. All nodes are working in half-duplex mode and the channels between T_1 and the relay, and T_2 and the relay are modeled as complex Gaussian random variables i^{th} distributions $h_{1r}\sim$ CN $(0,\sigma_1^2)$ and $h_{2r}\sim$ CN $(0,\sigma_2^2)$. Without loss of generality, we also assume channel reciprocity such that h_{r1} and h_{r2} have identical distributions as h_{1r} and h_{2r} , respectively. Odd and even time slots have equal length, which is the time to transmit one codeword, and are dedicated for uplink and downlink data transmissions, respectively. ACK and NACK control packets are assumed to be always successfully received and the trivial processing time is ignored. Additive Gaussian noise at the receiver terminals is modeled as n $\sim$ CN (0, σ_n^2).

3.4.1. Key assumptions

There are two more key assumptions:

1) Channel codes support communication at the instantaneous channel capacity levels, and outages, which occur if transmission rate exceeds the instantaneous channel capacity, lead to packet errors and are perfectly detected at the receivers;

2) Depending on whether packets are successfully received or not, ACK or NACK control frames are sent and received with no errors. Based on above network formulations, we can further discuss the TWRN working procedure according to the current network states under AF and DF relay schemes, and find out the inherent impact of the transmission rate R on network performances.

3.4.2 Amplify-and-forward TWRN

3.4.2.1 Network model:

The TWRN in AF mode can be visualized as two bi-directional cascade channels where in the odd time slots, $T_1$and T_2 send individual codewords simultaneously to the relay and the signals are actually superimposed in the wireless medium. The relay will then amplify the received signals proportional to the average received power and broadcast the combined signals back to $T_1$and T_2in the even time slots.

According to Figure 3.1, the received signals at the relay in odd time slots is,

$$y_r = \sqrt{P_1}h_{1r}x_1 + \sqrt{P_2}h_{2r}x_2 + n$$

Where, P_1= Transmit power of T_1

P_2=Transmit power of T_2

n = Gaussian noise component

The relay will forward $y_r$with a scaling factor β which is

$$\beta = \frac{\sqrt{P_r}}{\sqrt{P_1\sigma_1^2 + P_2\sigma_2^2 + \sigma_n^2}}$$

Where P_r is the relay's transmit power.

Here, we normalize the variance of the channel between $T_1$and T_2 as σ^2= 1 and by using a normalized distance factor,

$$k = \frac{d_{T_1,}Relay}{d_{T_1,}d_{T_2}} \in (0,1)$$

While assuming the variances of the other links are proportional to $d^{-\alpha}$

Where α = Path loss coefficient

Now we have,

$$\sigma_1^2 = k^{-\alpha}\sigma^2$$

$$\sigma_2^2 = (1-k)^{-\alpha}\sigma^2$$

At the end of even time slots, the received signals on $T_1$and T_2can be written as,

$$y_1 = \sqrt{P_1}\beta h_{r1} h_{1r} x_1 + \sqrt{P_2}\beta h_{r1} h_{2r} x_2 + \beta h_{r1} n + n_1$$

$$y_2 = \sqrt{P_1}\beta h_{r2} h_{1r} x_1 + \sqrt{P_2}\beta h_{r2} h_{2r} x_2 + \beta h_{r2} n + n_2$$

Wheren_1, n_2&$n$are Gaussian noise components.

Assuming the instantaneous channel state information is perfectly known at T_1andT_2, the self-interference part can be removed from y_1 and y_2 and the signals for decoding can be represented by

$$\hat{y}_1 = \sqrt{P_2}\beta h_{r1} h_{2r} x_2 + \beta h_{r1} n + n_1$$

$$\hat{y}_2 = \sqrt{P_1}\beta h_{r2} h_{1r} x_1 + \beta h_{r2} n + n_2$$

The cascade channel instantaneous rate from T_1 to T_2 and from T_2 to T_1 are hence represented by,

$$R_{12} = \log\left(1 + \frac{\left|\beta h_{r2} h_{1r}\right|^2 P_1}{(1 + \left|\beta h_{r2}\right|^2)\sigma_n^2}\right)$$

$$R_{21} = \log\left(1 + \frac{\left|\beta h_{r1} h_{2r}\right|^2 P_2}{(1 + \left|\beta h_{r1}\right|^2)\sigma_n^2}\right)$$

3.4.2.2 Network mechanism

Now to describe the network mechanism more accurately, we need to formulate the protocol of TWRN in AF mode as follows:

- Each transmission round contains two consecutive time slots. In the odd slot, source nodes T_1 and T_2 both transmit codewords to the relay with transmission rate R bit/sec/Hz, and the relay in the following even slot broadcasts βy_r back to source nodes.

- At the end of one transmission round, T_1 and T_2 perform self-interference cancelation (SIC) to subtract their own weighted messages, and decode by 1 and by 2, respectively. If the decoding fails, an outage event will be declared on that cascade link.

- The outage event on the cascade link $T_1 - T_2$ (or $T_2 - T_1$) is defined as the probability of the event $R_{12} < R$ (or $R_{21} < R$). ACK or NACK packets would be sent back to the relay based on successful transmission or outage. The relay will also notify T_1 and T_2 whether a new codeword or an old codeword should be (re)transmitted in the next odd time slot with the control packet information.

The network state transition diagram of the AF TWRN can be modeled as a Markov chain as shown in Fig. 3.2, where the probability on each path denotes the probability of the transition between two states. p_{12} and p_{21} are defined as the outage probabilities on the cascade $T_1 - T_2$ and $T_2 - T_1$ links and are given by,

$$p_{12} = p(R_{12} < R) = p\left(\frac{|h_{r2}h_{1r}|^2}{\frac{1}{\beta^2} + |h_{r2}^2|^2} < \frac{(2^R - 1)\sigma_n^2}{P_1}\right)$$

$$p_{21} = p(R_{21} < R) = p\left(\frac{|h_{r1}h_{2r}|^2}{\frac{1}{\beta^2} + |h_{r1}^2|^2} < \frac{(2^R - 1)\sigma_n^2}{P_2}\right)$$

Now the value of p_{12} and p_{21} can be determined using the cumulative distribution function of the random variable X given by,

$$F_X(x) = 1 - \frac{1}{\mu^2}\int_0^{\infty} e^{-\frac{x(a+z)}{\mu_1 z} - \frac{z}{\mu_2}}\, dz$$

Where,

$$X = \frac{Y_1 Y_2}{a + Y_2}$$

Y_1andY_2 are independent exponential distributed with mean μ_1 and μ_2, and a is a constant. In this context, we know

$$\begin{cases} \mu_1 = E\,[|h_{1r}|^2], \qquad \mu_2 = E\,[|h_{r2}|^2], \quad for\ \ p_{12} \\ \mu_1 = E\,[|h_{2r}|^2], \qquad \mu_1 = E\,[|h_{r1}|^2], \quad for\ \ p_{21} \\ \alpha = \dfrac{1}{\beta^2} \end{cases}$$

With the given network parametersp_{12} and p_{21} can be derived accordingly.

3.4.3 Goodput analysis:

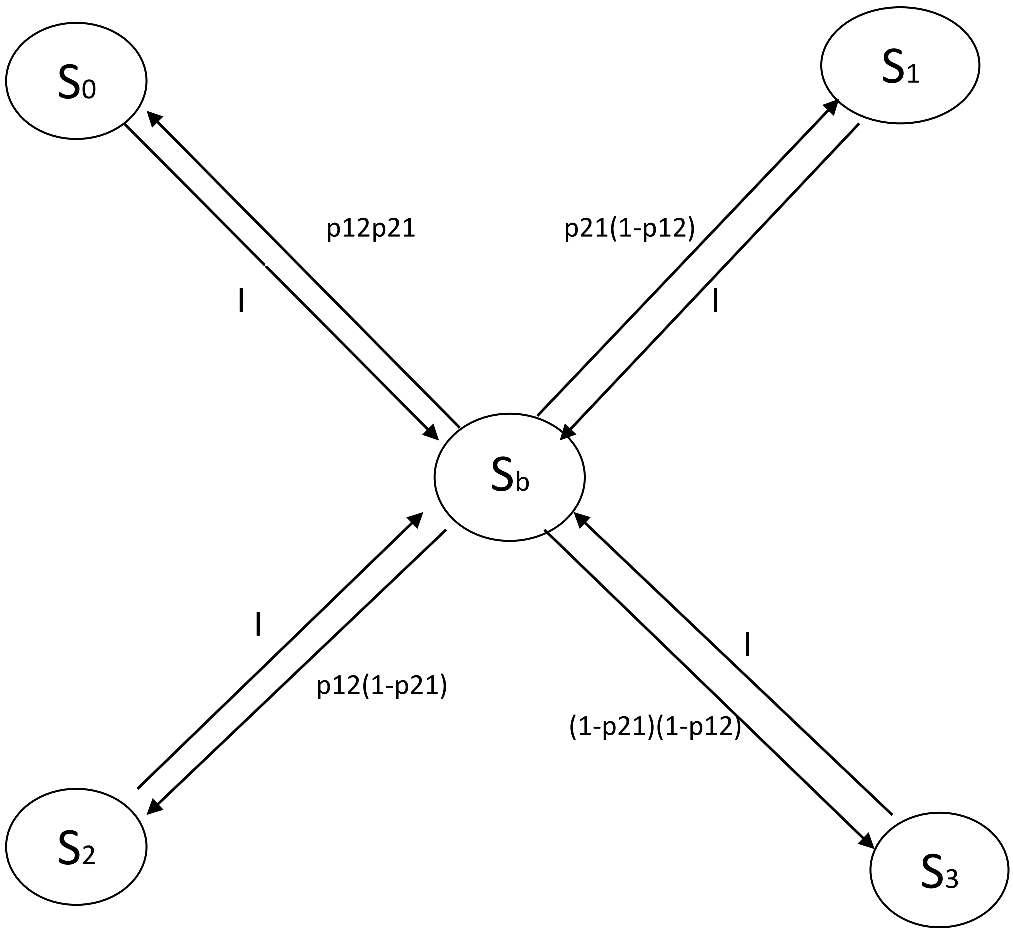

Figure 3.2: Markov Chain of TWRN in AF

In Figure 3.3, it is explicitly seen at the beginning of each odd time slot that both $T_1$and T_2transmit to the relay such that at the beginning of each even time slot, the relay is always in the ready-for-broadcasting state S b and will consequently transition to S_0, S_1, S_2, or S_3 with certain probabilities. We first determine the following four equations according to thestate transitions in the Markov chain to derive the probability of each state:

$$p(S_0) = p(S_b)p_{12}p_{21}$$

$$p(S_1) = p(S_b)p_{21}(1 - p_{12})$$

$$p(S_2) = p(S_b)p_{12}(1 - p_{21})$$

$$p(S_3) = p(S_b)(1 - p_{21})(1 - p_{12})$$

$$p(S_0) + p(S_1) + p(S_2) + p(S_3) + p(S_b) = 1$$

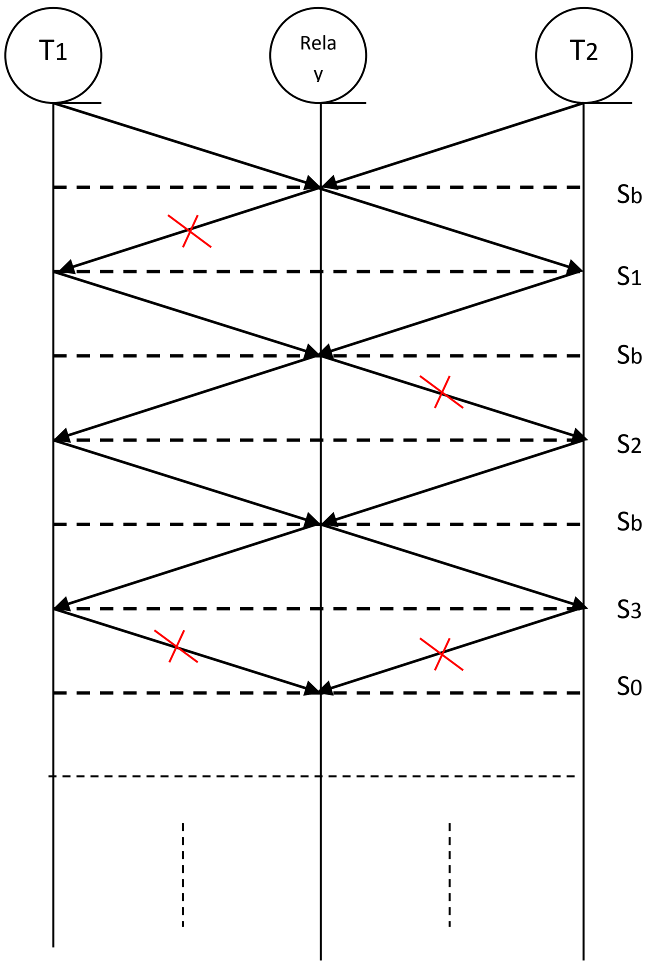

Figure 3.3: State Transition of TWRN in AF

After solving the set of equations, we obtain $(S_b) = \frac{1}{2}$. We know from the inherent characteristics of the AF TWRN that the data exchange only happens in the broadcasting phases with successful packet delivery. Therefore, the system goodput is defined by,

$$\eta_{AF} = p(S_b)R(2(1 - p_{12})(1 - p_{21}) + p_{12}(1 - p_{21}) + p_{21}(1 - p_{12}))$$

$$= \frac{R(2 - p_{12} - p_{21})}{2}$$

The above equation clearly indicates through the terms p_{12} and p_{21} that a higher transmission rate R will result in higher packet error rates (outage), leading to more ARQ retransmissions which equivalently reduce the data rate. Intuitively, a balance between transmission rate and the number of ARQ retransmissions needs to be found such that the goodput is maximized.

3.4.4 Average Bit Energy Consumption:

Energy efficiency has always been a major concern in wire-less networks. Recently, power or energy efficiency in wireless one-way relay networks have been extensively studied.

In [27], the average bit energy consumption E_b is minimized by determining the optimal number of bits per symbol, i.e., the constellation size, in a specific modulation format. Similarly as in one-way relay channels, the outage probabilities in TWRNs are functions of the transmission rate R .

For instance, there could be an increased number of outage events on the cascade channels whencodewords are transmitted at a high rate.

In such a case, more retransmissions and higher energy expenditure are needed to accomplish the reliable packet delivery. Therefore, we are interested in a possible realization of TWRN operation, which can provide a well-balanced performance on both the goodput η and the required energy.

We evaluate this by formulating the average bit energy consumption E_b required for successfully exchanging one information bit between $T_1$and T_2.

Here E_b is evaluated by considering long-term transmissions on TWRN. Regardless of the previous state, whenever the relay is in stateS_b and is broadcasting, the resulting state would be any of the other four states previously described.

Assuming there are K rounds of two-way transmission, each of which consists of a pair of consecutive time slots and each codeword has L bits.

Therefore,

With $\sum_{i=0}^{3} K_i = K$

Where K_i is the number of transmission round corresponding to state S_i,

The average bit energy consumption could be derived as the ratio of total bits successfully exchanged over total energy consumption:

$$E_b = \lim_{k\to\infty} \frac{K(P_1 + P_2 + P_r)\frac{L}{R}}{K_3 2L + K_1 L + K_2 L}$$

$$= \lim_{k\to\infty} \frac{(P_1 + P_2 + P_r)\frac{L}{R}}{\frac{K_3}{K} 2L + \frac{K_1}{K} L + \frac{K_2}{K} L}$$

$$= \frac{P_1 + P_2 + P_r}{(2 - p_{12} - p_{12})R}$$

3.5 Decode-and forward TWRN

3.5.1 Network model:

The DF TWRN differs from the AF TWRN in that there is a crucial intermediate decoding procedure at the relay when it has received the codeword from the uplink transmission.

If both source nodes are allowed to send codewords to the relay simultaneously in the uplink transmission, the decoding at the relay has to deal with the multiple access problem in a realistic application, with successive interference cancelation techniques.

To reduce the hardware complexity and increase the feasibility of implementation, we hereby adopt the DF TWRN mode from [21] where the relay performs sequential Decode-and-Forward. The outage probabilities on T_1- Relay, T_2- Relay, Relay $-T_1$, Relay $-T_2$links are denoted as p_{1r}, p_{2r}, p_{r1} and p_{r2}.

3.5.1.1 Protocol for sequential DF TWRN

The protocol for sequential DF TWRN is described as follows:

1. In the initial stateS_0, the relay's buffer is empty and the relay first polls on T_1 until it receives codeword $x_1$successfully with probability 1 − p_{1r}. Then, the state moves to S1 which means the relay holds x_1 in the buffer. Otherwise, the state remains as S_0 with probability p_{1r}.

2. If the relay already has x_1 , it starts polling T_2. The state S_1 either changes to S_3 with probability 1 − p_{2r} upon successfully receivingx_2, or stays in $S_1$with p_{2r}.

3. When the relay has both x_1 and x_2, it generates a new codeword,

$$y_{n}=\sqrt{\frac{P_r}{2}}x_1+\sqrt{\frac{P_r}{2}}x_2$$

   According to a Gaussian codebook of $2^{2\mathrm{LR}}$ with equal power allocation. Then at rate R, it broadcasts to $T_1$and T_2, which will perform SIC to decode x_2 and x_1 , respectively. Accordingly, the state will transit to, S_0, S_1 , S_2 or S_3 with corresponding probabilities $(1-p_{r1})(1-p_{r2})$, $(1-p_{r2})p_{r1}$, $(1-p_{r1})p_{r2}$ or $p_{r1}p_{r2}$ respectively

4. At the beginning of next transmission round, the relay will decide to poll a new codeword from T_1or T_2based on the previous state being S_0, S_2 $or S_1$ or just retransmits the old y_n if the previous state was S_3.

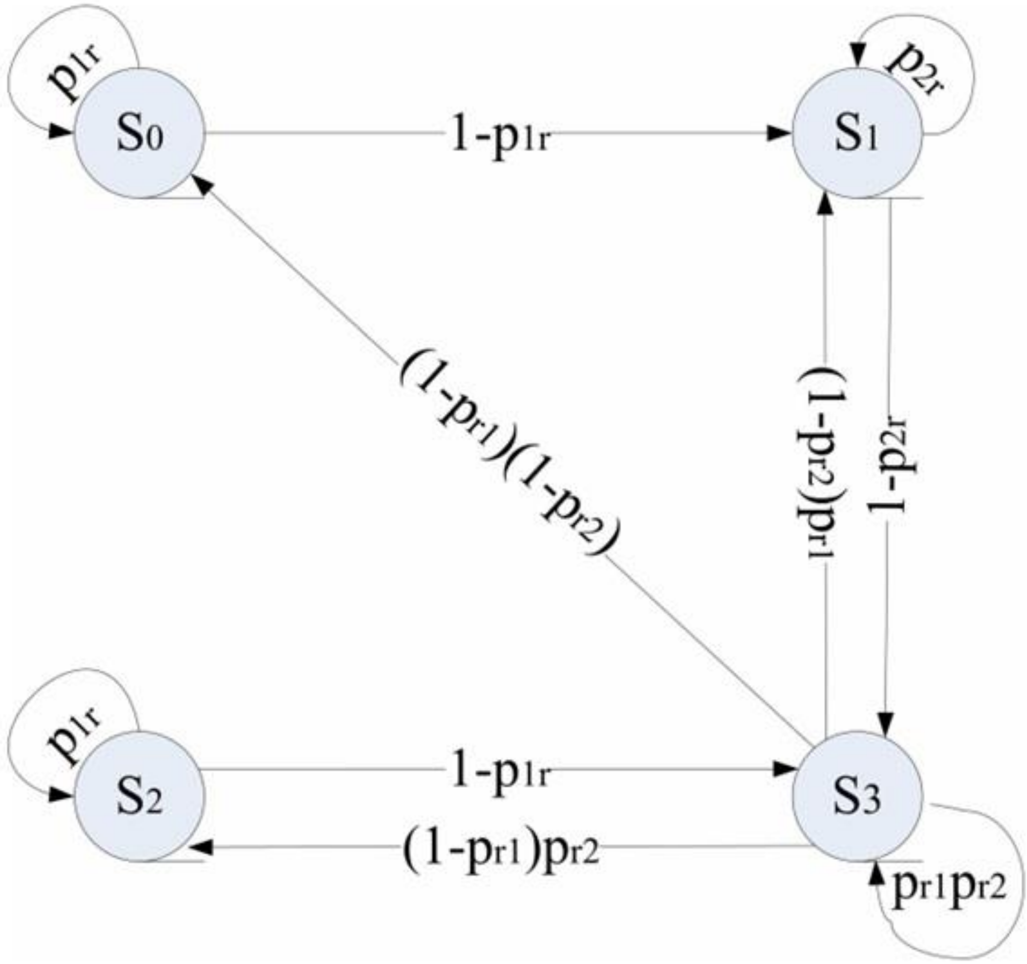

Figure 3.4: Markov Chain of TWRN in AF

The network state transition diagram of the DF TWRN can be modeled as in Figure 3.4 with detailed probabilities on each path. Since the relay receives and decodes x_1 and x_2 at different time slots, the received signals at the relay from uplink transmissions can be represented as,

$$y_{1r} = \sqrt{P_1} h_{1r} x_1 + n_1$$

$$y_{2r} = \sqrt{P_2} h_{2r} x_2 + n_2$$

The signals for decoding at T_1 and T_2 after SIC has been performed can be written as,

$$x_{r1} = \sqrt{\frac{P_r}{2}} h_{r1} x_2 + n_1$$

$$x_{r2} = \sqrt{\frac{P_r}{2}} h_{r2} x_1 + n_2$$

3.5.2 Goodpur analysis:

Similarly as in the discussion of the goodput of AF TWRN in Section III, the data exchange only occurs upon the successful signal receptions at T_1 and T_2at the end of the broadcasting time slot. Hence, initially, it is necessary to calculate the probability of being in state stays 3, i.e., $p(S_3)$We start from calculating the outage probabilities on the forward and backward channels as,

$$p_{1r} = 1 - e^{\frac{-(2^R-1)\sigma_n^2}{\mu_1 P_1}}$$

$$p_{2r} = 1 - e^{\frac{-(2^R-1)\sigma_n^2}{\mu_2 P_2}}$$

$$p_{r1} = 1 - e^{\frac{-(2^R-1)2\sigma_n^2}{\mu_1 P_r}}$$

$$p_{r2} = 1 - e^{\frac{-(2^R-1)2\sigma_n^2}{\mu_2 P_r}}$$

The probabilities of buffer states can be solved by noting the following relations from Figure 3.4

$$\begin{cases} p(S_0) = p(S_0)p_{1r} + p(S_3)(1-p_{r1})(1-p_{r2}) \\ p(S_1) = p(S_1)p_{r2} + p(S_3)(1-p_{r2})p_{r1} \\ p(S_2) = p(S_2)p_{1r} + p(S_3)(1-p_{r1})p_{r2} \\ p(S_3) = p(S_3)p_{r1}p_{r2} + p(S_1)(1-p_{2r}) + p(S_2)(1-p_{1r}) \end{cases}$$

Solving the equations with given outage probabilities, we can obtain the following results for the buffer states:

$$\begin{cases} p(S_0) = \frac{(1-p_{2r})(1-p_{r1})(1-p_{r2})}{D} \\ p(S_1) = \frac{(1-p_{1r})(1-p_{r2})}{D} \\ p(S_2) = \frac{(1-p_{2r})(1-p_{r1})p_{r2}}{D} \\ p(S_0) = \frac{(1-p_{1r})(1-p_{2r})}{D} \end{cases}$$

Where the polynomial in the denominators is denoted by

$$D = 3 - 2p_{1r} - 2p_{2r} - p_{r1} - p_{r2} + p_{r1}p_{2r} + p_{1r}p_{r2} + p_{1r}p_{2r}$$

Therefore, the system goodput in the DF mode can be derived as

$$\eta_{DF} = p(S_3)R(2(1-p_{r1})(1-p_{r2}) + p_{r1}(1-p_{r2}) + p_{r2}(1-p_{r1}))$$

$$= \frac{R(2-p_{12}-p_{21})(1-p_{1r})(1-p_{2r})}{p_{2r}p_{1r}+p_{r2}p_{1r}+p_{r1}p_{2r}+3-2p_{1r}-2p_{2r}-p_{r1}-p_{r2}}$$

3.5.3 Average bit energy consumption:

$E_b$in the DF TWRN is more complicated to calculate than in the AF TWRN where each transmission round has fixed power as can be seen. Hence, in the DF scenario, we have to separate the energy expenditure into two parts, energy consumption in the first stage and energy consumption in the second stage. The first stage denotes the state transition from any of 4 previous states to state S_3, where the relay holds two codewords x_1 and $x_2$in its buffer and is ready to broadcast. The second stage is that the relay broadcasts its newly generated codeword and the state transits back to any of the four states again.

Considering the relay's buffer is to be loaded with both code-words x_1 and $x_2$from any of the previous states on the first stage, the energy consumption conditioned on the previousstate $S_0,\ S_1,\ S_2\ or\ S_3$ on this particular transition will be,

$$E_{S_0} = \frac{P_1L}{(1-p_{1r})R} + \frac{P_2L}{(1-p_{2r})R}$$

$$E_{S_1} = \frac{P_2L}{(1-p_{2r})R}$$

$$E_{S_2} = \frac{P_1L}{(1-p_{1r})R}$$

$$E_{S_3} = 0$$

On the second stage, the energy consumption for broadcasting is always $\frac{P_R L}{R}$, so the average bit energy consumption for one information bit successfully exchanged on the DF TWRN can be computed as,

$$E_b = \frac{\sum_{i=0}^{3}\left(E_{S_i} + \frac{P_r L}{R}\right) p(S_i)}{\left(2(1-p_{r1})(1-p_{2r}) + (1-p_{r1})p_{r2} + (1-p_{r2})p_{r1}\right)L}$$

$$= \frac{E_{S_0}p(S_0) + E_{S_1}p(S_1) + E_{S_2}p(S_2) + \frac{P_r L}{R}}{(2 - p_{r1} - p_{r2})L}$$

Whenever the state probabilities and outage probabilities are known.

3.6 Numerical analysis:

In this section, we present the numerical results to evaluate the system performance of TWRN in both AF and DF modes. The network configurations are assumed to be as follows: Relay is located in the middle between T_1 and T_2which means k = 0.5. The power spectrum density of the Gaussian white noise is $\sigma_n^2 = 10^{-10}$and the channel bandwidth is set to $B = 10^6 Hz$. Path loss coefficient is α = 3.12 [28]. We also assume the same transmit power for both source nodes and the relay, which is $p_1 = p_2 = p_r = p$ and define the SNR by $\gamma = \frac{P}{\sigma_n^2}$

3.6.1 Goodputvs transmission rate R

Firstly, we are particularly interested in how the goodput varies as a function of the transmission rate R at specific SNR values. In Fig. 3.4, η_{AF} and η_{DF} are plotted as functions of R, with solid and dashed lines corresponding to AF and DF modes, respectively. On each curve with a given specific γ value, it's immediately seen that the goodput first increases within low R range and then begins to drop once the rate is increased beyond the optimal R∗which maximizes the goodputη. Additionally, at low values of the rate R, the AF TWRN has higher goodput η_{AF}, while beyond a certain rate R, DF starts to outperform, regardless of the SNR γ value.

3.6.2 Bit energy E_b vs transmission rate R

In Figure3.5, we analyze the energy efficiency. We notice that the difference of the average bit energy consumptions between two modes is insignificant up until R = 1, but DF stills has a better energy efficiency with a lower Ebregardless of γ. However when compared with the corresponding points (R <1) in Figure3.6, it is shown that even though DF can achieve a slightly lower E_b than AF, it also suffers a lower transmission efficiency in the metric of lower normalized rate. Above R = 1 in low SNR scenario of γ = 0, AF predominates with both higher normalized rate and lower $E_b$until R approaches about 6 bits/sec/Hz. Similar results can be observed on the high SNR scenarios also. In Figure 3.6, we study the impact of SNR on thenormalized rate in both AF and DF. Basically the normalized rate is increasing as SNR increases at all transmission rates. At low SNR e.g. R = −5 dB, DF performs better than AF. As SNR approaches R = 20 dB, the normalized rate gets close to 1 (or 0.7) in AF (or DF) mode. Consequently, one way to improve on the transmission efficiency is to increase SNR in the TWRN. Considering overall impacts of rate R and SNR, we can always find an scheme for the TWRN to achieve optimality in respect to the goodput Ƞ, the average bit energy consumption $E_b$or the transmission efficiency.

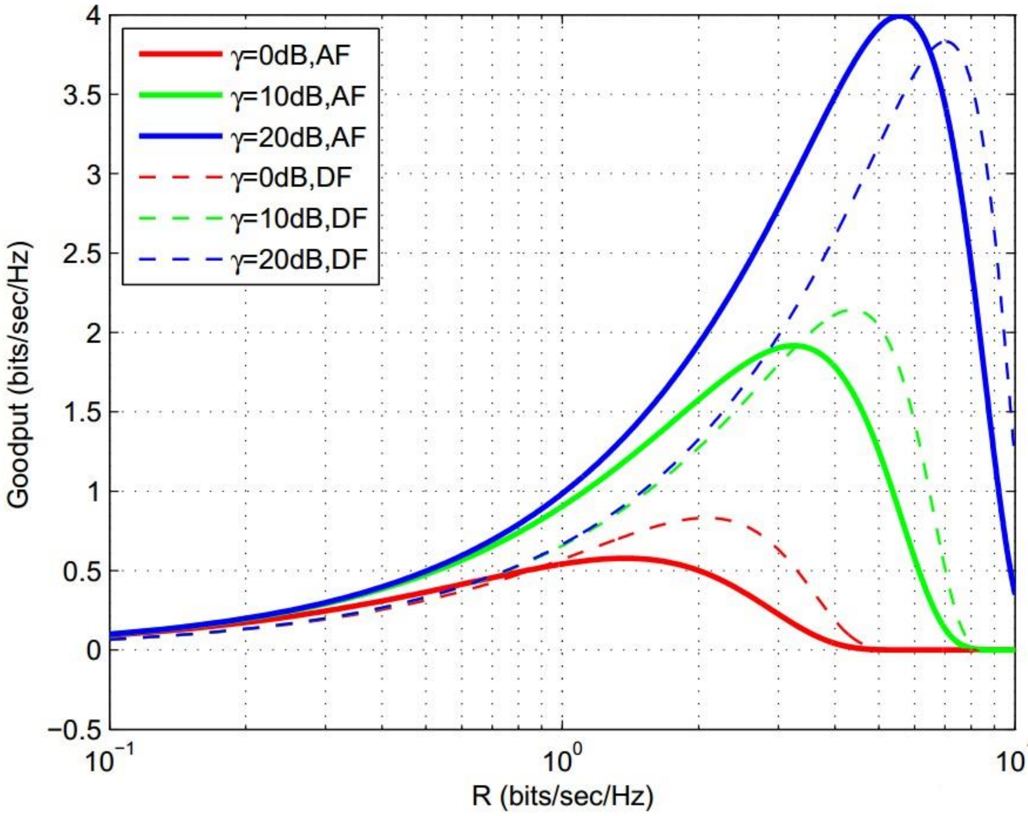

Figure 3.5:GoodputVs. Transmission Rate in AF and DF TWRN

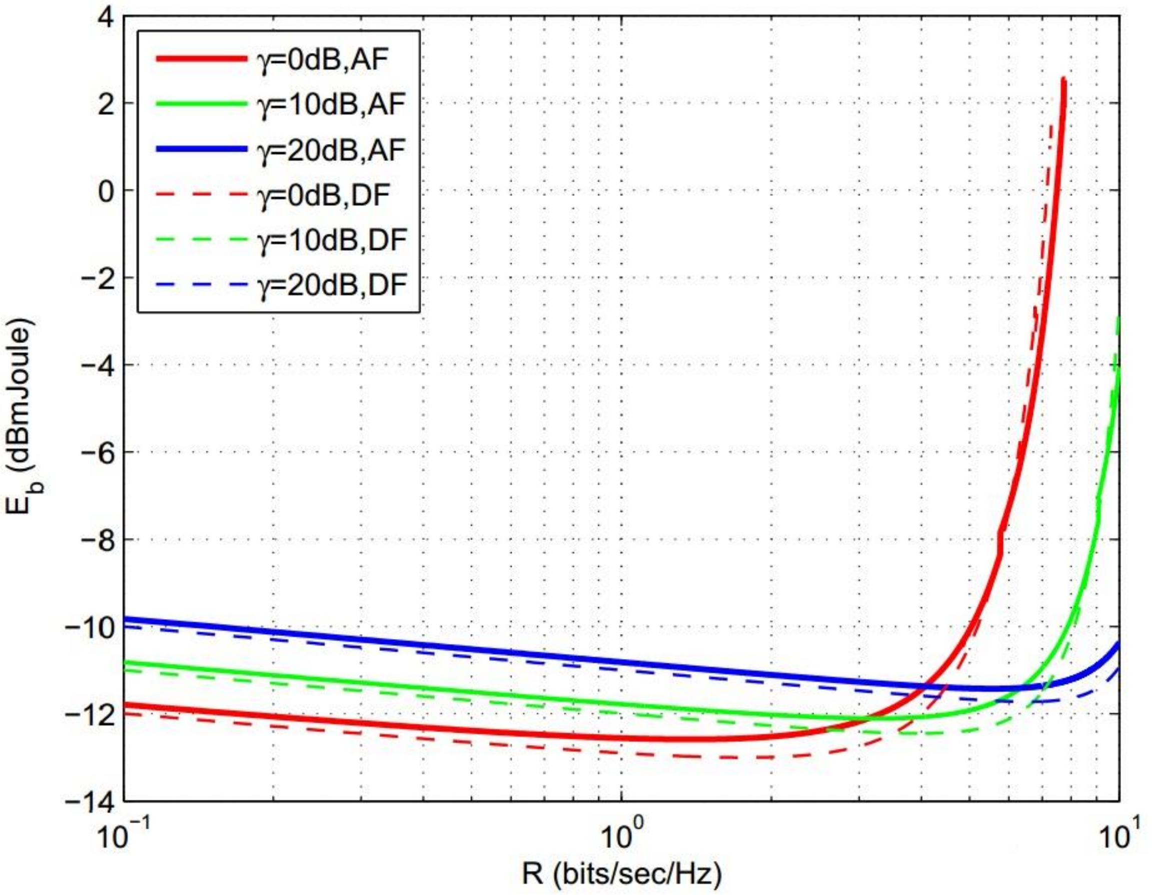

Figure 3.6:Average Bit Energy Vs. Transmission Rate

3.7 Conclusion:

So the two-way relay networks working in Amplify-and-Forward and Decode-and-Forward modes. In each mode, we set up a Markov chain model to analyze the state transition in details. ARQ transmission is employed to guarantee the successful packet delivery at the end and mathematical expressions for the goodput and bit energy consumption have been derived. Several interesting results are observed from simulation results:

1) The transmission rate R can be optimized to achieve a maximal goodput in both AF and DF modes.

2) Generally the transmission efficiency is higher in AF within a certain R range, while the DF can achieve a slightly higher energy efficiency instead.

3) Increasing SNR will always increase the normalized rate regardless of R. Hence, it's possible the network performance be optimized in a balanced manner to maintain a relatively high goodput aswell as a lowE_b.

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