



## AN ABSTRACT OF THE THESIS OF

Tingzhi Li for the degree of Master of Science in Electrical and Computer Engineering  
presented on December 8, 2016.

Title: Energy-Aware Gossip Techniques for Wireless Broadcasting

Abstract approved: \_\_\_\_\_

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The current state of research on gossip techniques for wireless broadcasting is very limited because past research efforts have mostly focused on using gossip techniques for multicast communication. On the other hand, those research efforts that have focused on using gossip techniques for wireless broadcast communications ignore energy efficiency and network lifetime. With the emergence of Internet of Things (IoT) devices, known with their limited energy and processing resource capabilities, energy consumption is becoming more and more important to account for when designing wireless broadcasting protocols. In this thesis, we propose a new energy-aware broadcasting protocol for wireless adhoc networks. Specifically, the proposed protocol dynamically adapts the fanout parameter based on wireless nodes' remaining energy to prolong the lifetime of the network. Our simulation results show that our proposed energy-aware gossip protocol outperforms existing approaches by achieving fast message broadcasting times while extending the nodes' battery lifetime.

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# Energy-Aware Gossip Techniques for Wireless Broadcasting

by

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A THESIS

submitted to

Oregon State University

in partial fulfillment of  
the requirements for the  
degree of

Master of Science

Presented December 8, 2016  
Commencement June 2017

Master of Science thesis of Tingzhi Li presented on December 8, 2016.

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## ACKNOWLEDGEMENTS

I would first like to thank my advisor Dr. Bechir Hamdaoui of the School of Electrical Engineering and Computer Science at Oregon State University. The door to Professor Hamdaoui office was always open whenever I had a question about my research or writing. I would like to express my gratitude to him for the useful remarks and engagement through the researching and writing process of this master thesis.

I would also like to thank Sherif Abelwahab for introducing me to the topic, providing great suggestions and answering my questions in many discussions. This research started as a team project in Advanced Computer Network class. Here, I would also like to acknowledge Marco Falke and Jinming Mu as initial project team members who participated in this project and in many ways shaped my research today.

Finally, I must express my very profound gratitude to my amazing parents Min Li, and Suling Han for their unfailing support and encouragement throughout my years of study abroad and through the process of researching and writing this thesis. This accomplishment would not have been possible without them. Moreover, I would like to thank my girlfriend Kendall Bailey for her unwavering support both during graduate school and my life.

# TABLE OF CONTENTS

	<u>Page</u>
1 Introduction	1
2 Related Work	4
3 Energy-Aware Gossip Protocol	7
3.1 Classic Gossip Protocol . . . . .	7
3.1.1 How It Works . . . . .	7
3.1.2 Key Gossip Protocol Control Parameters . . . . .	8
3.1.3 Variations of Gossip Protocol . . . . .	8
3.2 Our Basic Push-Pull Gossip Protocol . . . . .	10
3.3 Proposed Energy-Aware Adaptive Gossip Protocol . . . . .	13
4 Implementation	15
4.1 Basic Push-Pull Gossip Protocol Implementation . . . . .	15
4.1.1 ICMP Extension . . . . .	15
4.1.2 Source Node Implementation . . . . .	16
4.1.3 Gossip Nodes Implementation . . . . .	17
4.2 Adaptive Fanout Extension Implementation . . . . .	18
4.3 Simulation Control Program . . . . .	19
5 Performance Evaluation	24
5.1 Performance Metrics . . . . .	24
5.1.1 Average Network Lifetime . . . . .	24
5.1.2 Average Message Broadcast Time . . . . .	25
5.1.3 Average Overhead Per Node Per Message . . . . .	25
5.1.4 Average Energy Consumption Per Node Per Message . . . . .	26
5.1.5 Average Number of Broadcast Messages . . . . .	27
5.2 Simulation Environment Settings . . . . .	27
5.3 Result Analysis . . . . .	28
6 Conclusions and Future Work	34
Bibliography	35

## LIST OF FIGURES

<u>Figure</u>		<u>Page</u>
3.1	The pseudo code of our push-pull gossip protocol . . . . .	12
3.2	Adaptive fanout function plot . . . . .	14
3.3	The pseudo code of our adaptive fanout push-pull gossip protocol . . . . .	14
4.1	An example of how two gossip nodes communicate . . . . .	18
4.2	An example when two separate subnets formed . . . . .	20
5.1	Average message broadcast time vs. number of nodes . . . . .	29
5.2	Average network lifetime vs. number of nodes . . . . .	30
5.3	Average consumed energy per node per message vs. number of nodes . . .	31
5.4	Average overhead per node per message vs. number of nodes . . . . .	32
5.5	Average number of broadcast messages vs. number of nodes . . . . .	33



LIST OF TABLES

<u>Table</u>		<u>Page</u>
3.1	Gossip Protocol Category Matrix . . . . .	8
4.1	ICMP Header Structure . . . . .	16
4.2	ICMP Control Messages . . . . .	16
4.3	Our Gossip Protocol Extension . . . . .	16
5.1	Number of Simulations Run . . . . .	28

## Chapter 1: Introduction

Along with the development of the information technology, the price of the broadband connectivity becomes affordable. Devices are trending to be smaller and more powerful. People start to explore ways to connect devices to the network for better control and monitor the status of them. Devices such as smart phone, smart watch, smart thermostats, and radio-frequency identification (RFID) tags are able to connect to a network and these devices can communicate with each other. If these devices are connected to the Internet as well, we call them the *Internet of Things*. There is no doubt that IoT is an innovative paradigm [1] because this idea combined the Internet with our everyday gadgets. Either from the perspective of private user or from the perspective of business user, there are infinite possible ways to exploit IoT. As of today, research in the area of IoT is emerging rapidly and many open questions remain to be answered.

Many application services that IoT devices can provide rely on a network broadcast protocol to disseminating information [13]. For example, IoT devices firmware update package can be broadcast among devices in a distributed manner. However, the main challenge here is that IoT devices are often resource limited meaning they have limited bandwidth and energy, and restricted by their mobility. Due to the characteristics of IoT devices, topology of physical network formed from IoT devices is often dynamic. Therefore, a scalable, robust, and fault-tolerant broadcast protocol is needed for these dynamic networks. Flooding is consider to be the simplest broadcast protocol but it is not suitable. This is because flooding result in excessive overhead, media contention, and packet collision [24] which would severely deplete devices' precious battery power. Gossip techniques instead offer a relatively simple, robust, fast and probabilistic approach. This technique is inspired by the form of gossip seen in social network.

Besides gossip techniques, several deterministic approaches have been proposed which aim to reduce overhead by shifting message forward responsibility to a subset of nodes in the network [13]. However, there are two main problems for these approaches. First, if any node in the subset fails, nodes that depend on it will not be able to receive new messages[13]. Second, the energy nodes in those subset will be depleted sooner than

other nodes that are not the subset [13].

To properly define a variation of gossip technique, three main parameters need to be specified. They are *Probability of Gossip*, *Fanout*, and *Message Live Time*. With gossiping, nodes in the network have to forward the message with probability  $p_{gossip} \leq 1$  [13]. The idea is that a message can be broadcast successfully without every node's participation [13]. This approach can achieve a lower overhead because only a portion of the nodes participated in gossiping. However, the right  $p_{gossip}$  can be difficult to choose because global topology information is needed. Furthermore, an optimal  $p_{gossip}$  can become sub-optimal over time [13].

In terms of energy consumption, several adaptive energy based probabilistic schemes have been proposed. Most of them focused on dynamically adjusting  $p_{gossip}$  based on energy level related parameters. D. Nitnaware et. al proposed an adaptive gossip protocol based on node's energy level. When a node's energy level is above threshold, it will gossip the message with a fixed  $p_{gossip}$ . When a node's energy is below the threshold, it will drop the message. For a special case where a node only has one neighbor, the *Probability of Gossip* is set to be 1 regardless of its energy level [22]. This approach adjusts *Probability of Gossip* in a very coarse manner since a node would only operate in one of two states: gossip with a fixed probability, or drop incoming new messages. In [19], node's remaining energy fraction is used directly as *Probability of Gossip*. Clearly, this is more fine-tuned than [18].

However, none of these efforts focused on another key gossip technique parameter: *Fanout*. From our observation, for any given *Probability of Gossip*, higher *Fanout* setting allows nodes to contact more neighbors each round thus achieve a faster message broadcast time. But higher *Fanout* setting usually is associated with higher energy consumption. On the other hand, lower *Fanout* setting conserves nodes' battery power but takes longer to broadcast a message. Our aim in this thesis is to retain the benefit of high *Fanout* setting (fast message broadcast time), and increase the lifetime of the network. Therefore, we proposed a gossip broadcast protocol that can dynamically adjust *Fanout* parameter based on each gossip node's remaining energy level.

The rest of this thesis is organized as follows. We present related work in Chapter 2. Chapter 3 describes the classic gossip protocol, our basic push-pull gossip protocol, and our proposed energy-aware adaptive fanout extension. Chapter 4 presents the implementation of our energy-aware gossip protocol. We present performance evaluation

in Chapter 5, and conclusion and future work in Chapter 6.

## Chapter 2: Related Work

Over the years, gossip techniques have proven to be the corner stone for building scalable and robust distributed computer network systems. This technique is often used to design multicast protocol [7] [10], routing protocol, and broadcast protocol. Demers et. al [5] demonstrated the advantages of deploying this technique in corporation for database maintenance in the early days. In recent years, this technique has been utilized in wired networks [2] as well as in wireless networks. Many proposed schemes whether is for wired networks or is for wireless networks, all focused on optimizing protocol overhead, or energy consumption. The metrics they used include network density, or nodes' energy level.

In wired network domain, it has being used for peer-to-peer network [7]. In wireless network domain, it has being used for mobile ad-hoc networks [4] [25], and wireless sensor networks [15] [17]. There are many proposed schemes that are designed for wired network that uses network information for adaptive gossiping such as [11] [23], but those approaches are not suitable for wireless networks [13].

Some of the basic gossip techniques that are specifically designed for wireless networks includes fixed forward probability scheme [8] where each node has the probability of  $p$  to gossip the message to its neighbor while it has the probability of  $1 - p$  to not gossip the message to its neighbor. Because in this paper the authors are designing a routing protocol in a wireless ad-hoc network, each time when a node receives a new message, it will only pick one of its neighbors. In other words, the *Fanout* here is set to be 1. The advantage of this proposed scheme is that it is easy to implement in practice. However, due to the dynamic nature of mobile ad-hoc network or wireless sensor network, a fixed forward probability can be difficult to choose. Moreover, even an optimal forward probability may become sub-optimal over time.

To address the disadvantage of a fixed forward probability scheme, Cartigny et. al [3] proposed a new broadcast scheme for ad-hoc networks that would adjust *Probability of Gossip* based on number of neighbors a node has. The equation for calculating *Probability of Gossip* is  $p_{gossip} = \frac{k}{n_b}$  where  $k$  is the propagation factor and  $n_b$  is a node's

degree (number of neighbors). The minimum and maximum *Probability of Gossip* can be adjusted by changing propagation factor. The idea is that a node with more neighbors will have a lower probability to gossip new messages and vice versa. This scheme reduced overhead by tailoring *Probability of Gossip* for each node but a suitable  $k$  value for various ad-hoc network topologies can still be difficult to choose.

Another interesting proposed gossip broadcast scheme is called "Smart Gossip" [13]. It uses "family classification" method to category a node's neighbors. A node's neighbor can be classified in one of three categories: parent, sibling, or child. Intuitively, the more siblings a node has, the lower the *Probability of Gossip* will be because other siblings may have transmit the new message to the child [22]. Moreover, *Probability of Gossip* is proportional to number of children a node has [22]. When a node has no child, the  $p_{gossip} = 0$ . When a node has no siblings but only child, the  $p_{gossip} = 1$ . This advantage of this approach is that it takes nodes dependency into account while gossiping. However, this scheme can be complicated to implement and there is no update after the initial hierarchy establishment [22].

In terms of reducing energy consumption while using gossip techniques, Nitnaware et. al [18] proposed a simply scheme by defining a *Energy Level Threshold*. When a node's energy level drops below the threshold, this node will not gossip new messages it received. Otherwise, it will gossip the new message with the probability of  $k$ . One special case is that when a node only has one neighbor, it will gossip the new message with probability of 1 regardless of its energy level. In [19], the authors proposed to use the remaining energy fraction directly as *Probability of Gossip*. So the gossip probability is defined as  $p_{gossip} = \frac{E_{frac}}{100}$ . A node with higher remaining energy fraction will have a higher gossip probability. A more advanced energy-aware gossip based broadcast scheme is proposed by Reina etl. al in [21]. In this paper, the authors proposed to calculate a node's *Probability of Gossip* according to the following equation:  $p_{gossip} = \frac{E_i - E_{min}}{E_{max} - E_{min}}$  where  $E_i$  is the node's energy level,  $E_{max}$  is the maximum energy level among its neighbors, and  $E_{min}$  is the minimum energy level among its neighbors. This approach requires nodes to insert their energy level information when requesting for a message update. This scheme is similar comparing to "Smart Gossip" in terms of collecting neighbors information instead of focusing on the information a node itself can obtain.

One thing all these paper have in common is that they all focused on adjusting *Probability of Gossip* to reduce protocol overhead or reduce protocol energy consumption.

They never explore the possibilities of adjusting *Fanout* to achieve longer network lifetime. Because some of the paper that mentioned here focused on designing a routing protocol, a *Fanout* setting of 1 is the common practice. A higher *Fanout* is unlikely to improve routing protocol performance and is more complicated for a protocol to maintain the routing table.

## Chapter 3: Energy-Aware Gossip Protocol

In this chapter, we will first introduce the classic gossip protocol which will serve as a base protocol for other variations of gossip protocols. Then we will explain the detail of our basic push-pull gossip protocol. And lastly, we will introduce our proposed energy-aware gossip protocol which is based on the basic push-pull gossip protocol.

### 3.1 Classic Gossip Protocol

#### 3.1.1 How It Works

The objective of gossip protocol is to broadcast messages in an efficient manner by mimicking social activities when people spread rumors in office by gossiping among each other. The classic gossip protocol works as follows: when a node had a new message, it will send it to multiple randomly picked nodes in the network. Every node that received the new messages then will each randomly select multiple nodes and share the message with them. After a couple rounds of gossiping, majority of the nodes in the network have received this new message. The number of nodes a node tried to contact is defined as the *Fanout* of gossip protocol. It is denoted as  $f$ . Each time when a node face the decision of whether sending a new message to another node or not, the probability of doing so is defined as  $p_{gossip}$ . In the rest of this thesis, I will refer to *Probability of Gossip* as  $p_g$ . Once a node received a new message, the number of times it will contact other nodes is defined as the *Message Live Time* of gossip protocol. It is denoted as  $T_l$ .

In a wired network setting, the *Probability of Gossip* of classic gossip protocol is set to be 1 and *Fanout* is usually set to be 1 or 2. *Message Live Time* could vary depending on the application requirement. In a wireless ad-hoc network setting, a simple broadcasting by flooding would cause *broadcast storm* problem [24]. Due to overlapping radio signals in a geographical area, flooding often cause excessive redundancy, serious contention, and collision. Instead *Fanout* is set to be 1 or 2 as well. However, people often tweak *Probability of Gossip* based on local or global network information such as



total number of nodes, or node's degree (number of neighbors). Their goal is to reduce protocol overhead by lowering *Probability of Gossip* while still achieving decent message broadcasting coverage.

### 3.1.2 Key Gossip Protocol Control Parameters

Four key parameters that define the behavior of gossip protocol in a wireless ad hoc network are:

- *Probability of Gossip*:  $p_g$  ( $0 < p_g \leq 1$ )
- *Fanout*:  $f = 1, 2, 3, \dots$
- *Message Live Time*:  $T_l = 1, 2, 3, \dots$
- *Gossip Interval*  $\Delta T_g$  (applicable when  $T_l > 1$ )

When  $p_g = 1$  and  $f = \text{node's degree}$ , this protocol is closely resemble to flooding broadcast scheme which is not suitable for wireless ad hoc network. When  $p_g = 1$  and  $f = 1$  or  $2$ , this protocol is set to be classic gossip protocol.  $T_l$  is a parameter that is closely related to a node's memory constrain. A large  $T_l$  setting will increase the message broadcasting successful rate at the expense of higher memory requirement and greater protocol overhead.

### 3.1.3 Variations of Gossip Protocol

It is more clear when we category different variations of gossip protocol into a matrix as shown in Table 3.1.

Table 3.1: Gossip Protocol Category Matrix

	Global Network Information	Local Network Information
Fixed $p_g$	<b>Quadrant I</b>	<b>Quadrant II</b>
Adaptive $p_g$	<b>Quadrant III</b>	<b>Quadrant IV</b>

The *Probability of Gossip* can be set to a fixed value or be adaptive. The basis of calculating  $p_g$  can either be local network information such as node's degree (number

of neighbors) or global network information such as number of nodes in the network. Therefore, we have four quadrants in this matrix.

- **Quadrant I:** fixed  $p_g$  based on global network information.
- **Quadrant II:** fixed  $p_g$  based on local network information.
- **Quadrant III:** adaptive  $p_g$  based on global network information.
- **Quadrant IV:** adaptive  $p_g$  based on local network information.

One observation is that researchers mainly focused on adjusting *Probability of Gossip*. Very little attention has been paid to another gossip protocol parameter *Fanout*. Fixed *Probability of Gossip* approaches can calculate its probability based on network density, distance among nodes, and speed [22]. In this scheme, nodes forward an incoming message with a fixed  $p_g$ , and the probability of not forwarding the incoming packet is  $(1 - p_g)$  [22]. The major challenge of fixed scheme is determining the optimal  $p_g$ . Due to the dynamic nature of wireless ad-hoc network, even an optimal initial global  $p_g$  could become sub-optimal overtime.

Adaptive *Probability of Gossip* approaches uses local or global network information such as density and speed to adjust individual or global probability. In adaptive scheme, there are adaptive non-counter-based schemes and adaptive counter-based schemes [22]. Adaptive density-based schemes usually utilize node's degree metrics. In (nb-scheme) the  $p_g$  has an inverse relationship with the number of neighbors of a node [3]. If we denote node's degree as  $n_b$ , then

$$p_g = \frac{k}{n_b} \quad \text{where } k \text{ is the propagation factor}$$

The  $k$  is used so that the maximum and minimum probability can be adjusted [3]. The basic idea behind this approach is that for a node with higher node's degree (meaning it has more neighbors, thus this area is more dense), a lower *Probability of Gossip* will be sufficient to spread out the new message. While for an sparse area, higher *Probability of Gossip* would be more desirable. Some paper [20][26] suggested schemes that dynamically adjust *Probability of Gossip* based on Received Signal Strength (RSS) or euclidean distance. In [26], the authors denoted the relative distance between node  $i$

and node  $j$  by  $D_{ij}$  and the average transmission range by  $r$ . The *Probability of Gossip* is calculated using the following equation:

$$p_g = \frac{D_{ij}}{r}$$

For a given  $D_{ij}$ , wider average transmission range will result in a lower *Probability of Gossip*. On the other hand, for a given average transmission range, *Probability of Gossip* will increase when the distance between node  $i$  and node  $j$  gets greater.

In counter-based schemes, nodes keep track with number of received copies of a given broadcast message and use it to determine its broadcasting state [22]. Similar to non-counter-density-based schemes, some paper [14] used node's degree in conjunction with a counter. The equation used to calculate *Probability of Gossip* is as follows:

$$p_g = \frac{p_i}{n_b} \quad \text{where } p_i \text{ is the initial Probability of Gossip}$$

The initial probability is set to be 1. If we denote the copy of messages threshold by  $m_{th}$  and number of received copies of a given broadcast message by  $m_r$ , then whenever  $m_r \geq m_{th}$ , the above equation starts to kick in.

Similar to non-counter-distance-based schemes, some paper [12][16] used the distance between nodes as a metrics combining with a counter to determine the broadcasting state a node should be in.

### 3.2 Our Basic Push-Pull Gossip Protocol

When each node in the network forward new broadcast messages when it receive one, it is called a *push* gossip protocol. Similarly, when each node only request for new broadcast messages from other nodes, it is called a *pull* gossip protocol. Our gossip protocol combined both mechanisms thus it is called a *push-pull* gossip protocol.

Our basic push-pull gossip protocol utilizes three packet types to perform. They are:

- Data packet
- Ack packet
- Request packet

Data packet carries the actually payload (broadcast message). Ack packet and Request packet are used to control gossip process. There are several rules in our push-pull gossip protocol. The Ack packet is used to acknowledge to the sender that receiver node already received that message before. The Request packet is used for a node to ask for the latest message from another node.

- Rule 1: A node can only be in two states – sleep state, and gossip state.
- Rule 2: Periodically, a node will request for a new message from one randomly selected neighbor regardless of its state.
- Rule 3: When a node received a new broadcast message, it will enter the gossip state.
- Rule 4: When a node is in gossip state, it will periodically randomly select  $\min(f, n_b)$  neighbors and forward the message to them.
- Rule 5: When a node received an Ack packet from any of its neighbor, it will enter sleep state which mean it will stop gossiping the new message.
- Rule 6: When a node received a duplicate message from another node, it will send an Ack packet back.

The pseudo code of our push-pull gossip protocol is given in Figure 3.1. All nodes in the network follow the same rules described above. For the sake of discussion, we assume that  $f = 1$  and there is no isolated node in the network. In the background, every node in the network will run a request process every 5 seconds regardless of its state. During the request process, it will randomly select a neighbor and request it to send its latest message. Initially, every node is in sleep state. Now let's assume that a new broadcast message is generated by node 1. Then node 1 immediately switch from sleep state to gossip state and start sending out this message to one of its neighbors. This gossip process runs every 5 seconds unless the node switched to sleep state. When a node switched to sleep state, it will do nothing. Now when a node received a Data packet, it will check for duplication. If it is indeed a new message, it will store the message and switch to gossip state. If it is not a new message, it will send an Ack packet back to the sender. If a node received an Ack packet, it will switch to sleep state. Lastly, if a node received a Request packet, it will send its latest message back to the sender.

```

// Periodic request
if state == gossip or state == sleep:
    every 5 seconds:
        find a random neighbor N
        send a Request packet to N

// Periodic gossip
if state == gossip:
    every 1 second:
        find min(f, node's degree) random neighbors N<vector>
        send Data packet to N<vector>

if state == sleep:
    Do nothing

// Handle packets
if receive a Data packet:
    if it is a new one:
        store the message
        state <- gossip
    else
        send an Ack back
if received an Ack packet:
    state <- sleep
if received a Request packet:
    send the latest message back

```

Figure 3.1: The pseudo code of our push-pull gossip protocol

### 3.3 Proposed Energy-Aware Adaptive Gossip Protocol

As we stated previously in the thesis, the current state of research on gossip techniques for wireless broadcasting focused very little on energy efficiency and network lifetime. Far too many researches focused on dynamically adjusting  $p_g$  based on global or local network information (global: number of nodes, local: node's degree, overhearing). Our objective here is to develop a new energy-aware gossip protocol that could extend network lifetime while still achieving a fast and reliable broadcasting performance. The parameter that we focused on shifted from *Probability of Gossip* to *Fanout*.

Our observation tells us that a higher *Fanout* setting will result in a shorter broadcasting time for a new message at the expense of higher energy consumption. While a lower *Fanout* setting conserves energy, it results in a longer broadcasting time. First of all, we argue that each node's battery life should be maximized in order to extend network lifetime. Since for a broadcasting protocol, any node that is disconnected from the network due to energy depletion renders a situation that broadcasting can no longer work. In order to maximize each node's battery life, a constant high *Fanout* setting is undesirable when battery is very low. Similarly when battery is very high, a constant low *Fanout* setting can hinder the message broadcasting time. Therefore, we proposed that *Fanout* should be dynamically adjusted based on each node's remaining energy fraction.

Let's denote the *Remaining Energy Fraction* as  $E_{frac}$ . The function that used to calculate *Fanout* is defined as follow:

The function is plotted in Figure 3.2.

The basic idea of our fanout function is that the *Fanout* of a node will gradually stepping down as its battery energy being drained. We believe this new fanout function can combine the advantages of both worlds. When a node's has plenty of energy left, it will reach out to more neighbors and facilitate message broadcasting process. As a node's energy gets lower, it will conserve its battery energy by contacting less neighbors thus extend network lifetime.

Now we could tweak our basic push-pull gossip protocol that we explained in Section 3.2 based on the proposed fanout function. The pseudo code of adaptive fanout push-pull gossip protocol is given in Figure 3.3. Every time when a node tries to gossip a new message, it will first calculate the *Fanout* using the adaptive fanout function. One thing that worth mentioning here is that *Fanout* cannot exceed its node's degree. So here we

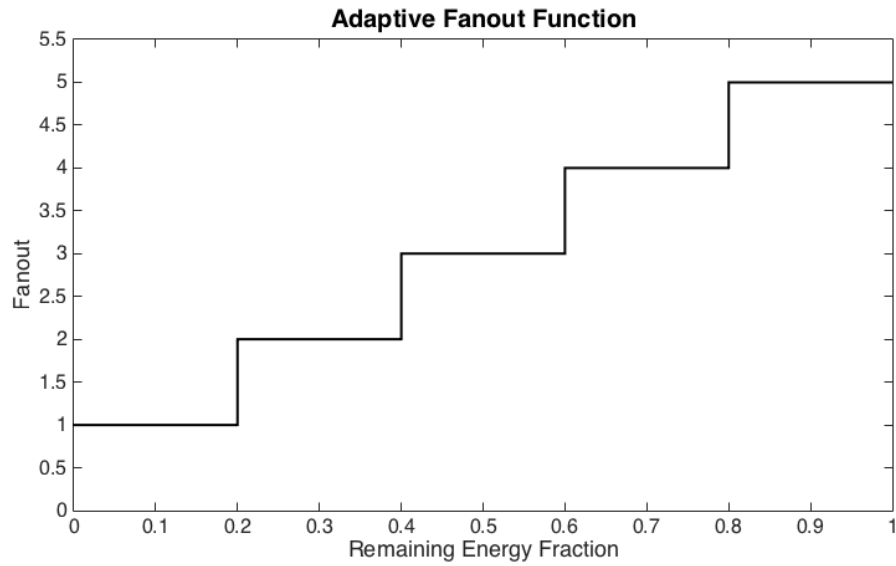


Figure 3.2: Adaptive fanout function plot

```
// Periodic gossip
if state == gossip:
    every 1 second:
        calculate the fanout f based on its energy fraction
        find min(f, node's degree) random neighbors N<vector>
        send Data packet to N<vector>
```

Figure 3.3: The pseudo code of our adaptive fanout push-pull gossip protocol

have to take the minimum number between the calculated *Fanout* and node's degree. For example, if a node only has 3 neighbors but the result from the fanout function is 5, the actual *Fanout* will be 3.

## Chapter 4: Implementation

In order to evaluate our proposed energy-aware gossip broadcasting protocol, we implemented the protocol in a open-source software called Network Simulator 3 (ns-3). From system point of view, this whole implementation consists of 4 major parts. They are the ICMP extension, the adaptive fanout push-pull gossip protocol, the UDP server and client application, and the simulation control program. The ICMP extension is the necessary backbone gossip communication infrastructure developed to support adaptive fanout gossip protocol in application layer. The adaptive fanout gossip protocol is the protocol entity that we are interested in studying. It utilized underlining ICMP extension to communication among gossip nodes. It controls our proposed adaptive fanout gossip protocol's logic and behavior. The UDP server and UDP client are installed on source node and gossip nodes respectively. This provides a channel to collect simulation data. Lastly, the simulation control program is developed to handle simulation environment set up, start and stop simulation, and process and output collected data.

### 4.1 Basic Push-Pull Gossip Protocol Implementation

#### 4.1.1 ICMP Extension

For the basic push-pull gossip protocol implementation, we first started building those 3 types of packets (Data packet, Ack packet, and Request packet) by extending the existing Internet Control Message Protocol (ICMP). The most common use of ICMP is for error reporting [9]. An ICMP message contains two parts: 8-byte header and data section. The first 4 bytes of the header have a fixed format. However, the last 4 bytes vary and depend on the type or code of the ICMP packet [6]. The first and second byte of the header is the type field and code field respectively. And the third and fourth byte are checksum field. The format of the header is shown in Table 4.1.

Table 4.2 here presented some of the selected ICMP message types.

Since type 42 to 255 are reserved for further development, we decided to extend



Table 4.1: ICMP Header Structure

Octet	0	1	2	3
	Type	Code	Checksum	
Octet	4	5	6	7
	Rest of Header			

Table 4.2: ICMP Control Messages

Type	Code	Description
0	0	Echo reply
8	0	Echo request
9	0	Router Advertisement
10	0	Router discovery/selection/solicitation
42 to 255		Reserved

ICMP by defining type 42, 43, and 44 to represent Ack packet, Request packet, and Data packet respectively. The detail is shown in Table 4.3.

Table 4.3: Our Gossip Protocol Extension

Type	Code	Description
42	0	Send Acknowledgment
43	0	Send Request
44	0	Send Data

Based on these new control message types extension, we could further develop our basic push-pull gossip protocol in ns-3. ICMP is a layer 3 protocol, but the actual control logic of our gossip protocol is developed in application layer.

#### 4.1.2 Source Node Implementation

In order to generate and collect simulation results, the system consists of a source node and  $n$  gossip nodes. The source node is responsible for the following duties:

- Generate new broadcast messages
- Store time stamps for each generated new messages

Every time when a new broadcast message is generated, it will send it to one of the gossip nodes via a special pair of wireless ad-hoc network thus kick start the broadcasting process. Except the first broadcast message, every other new broadcast message will only be generated and sent out when it received  $n$  *Acknowledgment packet* (different from the Ack packet) from all gossip nodes for the previous broadcast message. Because in the program, we make sure that each gossip node will only send this special *Acknowledgment packet* once per broadcast message, it is a good indication that this broadcast message has been successfully broadcast. In order to support this feedback mechanism, we deployed an UDP server application so that every gossip node can connect to it and send its *Acknowledgment packet*. It is worth noting that the actual implementation of a source node is a streamlined gossip node implementation with functions in the receiving end and the ability to send Ack packets and Request packets disabled.

### 4.1.3 Gossip Nodes Implementation

For gossip nodes, as shown in Figure 3.1, there are two main processes. The periodic request processes and periodic gossip processes. At the start of the simulation, these two processes will be initialized. Most of the functionalities for a gossip node belong to either receiving end or transmitting end. In receiving end, we developed functions to handle Ack packet, Request packet, and Data packet. In the transmitting end, we developed functions to send Ack packet, Request packet, and Data packet. Besides, we also deployed an UDP client application on these gossip nodes so that it can send time stamps of each broadcast message back. To make all these functionalities work, these functions actually call the corresponding functions in ICMP as we described earlier. For example, if a gossip node is trying to send a new broadcast message to another gossip node, it would first call the function *sendPayload()* that is in application layer. Then *sendPayload()* would have to call the function *sendMessage()* in ICMP which is in network layer. On the receiving end, a node first would receive the new broadcast message in network layer. The message is handled by a function in ICMP called *handleData()*. Then in turn, this function will call the corresponding function in the application layer. The whole process is illustrated in Figure 4.1.

In summary, gossip nodes has the following responsibilities:

- Gossip every new broadcast message

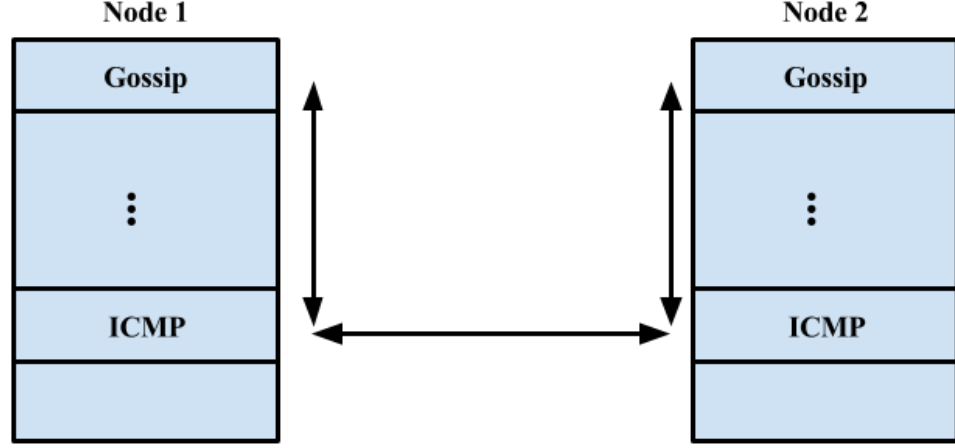


Figure 4.1: An example of how two gossip nodes communicate

- Store every broadcast message without duplication
- Store the time stamps for each received new broadcast message
- Report each new broadcast message time stamps back to the source node

## 4.2 Adaptive Fanout Extension Implementation

To add our proposed adaptive fanout scheme into the existing push-pull gossip protocol, we first aggregated a basic energy source to each gossip node. Then we utilized WiFi radio energy model to simulate the energy consumption for each gossip node when transmitting or receiving a packet. The basic energy source increase or decrease its remaining energy linearly. The WiFi radio energy model has 4 states defined. They are TX, RX, IDLE, and SLEEP. The power consumption of each state in Watts are defined as follow:

- $P_{tx} = 1.14$
- $P_{rx} = 0.94$
- $P_{idle} = 0.82$
- $P_{sleep} = 0.10$

In our implementation, we actually set  $P_{idle} = 0$  and  $P_{sleep} = 0$  because majority of the time when a node participated in broadcasting a message, it stays in the IDLE state. Therefore, if we don't disable  $P_{idle}$  and  $P_{sleep}$ , the network lifetime will be largely determined by  $P_{idle}$  which is undesirable. Once we have energy sources and Wifi radio energy model installed on the gossip nodes, we then can calculate the corresponding *Fanout* for each node. One small detail worth mentioning here is that the actual *Fanout*  $f_{actual}$  cannot exceed a node's degree (number of neighbors)  $n_b$ , thus  $f_{actual} = \min(f, n_b)$ . Once we have the *Fanout* information, the rest gossip process works as described in Section 4.1.

### 4.3 Simulation Control Program

As we stated earlier in this chapter, the simulation control program is here to properly set up simulation environment, initialize simulation objects, start and stop simulation, and collect, process, and export simulation data.

For the simulation environment set up, because we want to collect simulation data about network lifetime, the simulation stop time is set to be large enough so that the energy source will be depleted first. Any depleted energy source will automatically trigger the simulation to stop. Topology wise, we wanted it to be a close resemble to Wireless Sensor Network (WSN) or MANET. In other words, we wanted to avoid gossip nodes cluster in a small area. We achieve that goal by adopting a small maximum WiFi range for each gossip node and scale up nodes' placement area as number of nodes increases. Since an area with dimension of  $100m \times 100m$  with  $50m$  maximum WiFi range can achieve a desirable network density for 10 gossip nodes, we used this ratio to calculate the dimension of nodes placement area. If we denote the side of a square area by  $s$ , then the equation to calculate the size of the nodes placement area is as follows:

$$s = \sqrt{1000 \times n} \quad \text{where } n \text{ is number of gossip nodes}$$

Because of random gossip nodes placement and a fixed maximum WiFi range, a newly generated topology could contain isolated nodes that no other nodes can contact. In this case, we cannot achieve successful broadcasting no matter what we do. Another possible case is shown in Figure 4.2 where a network is divided into two separated

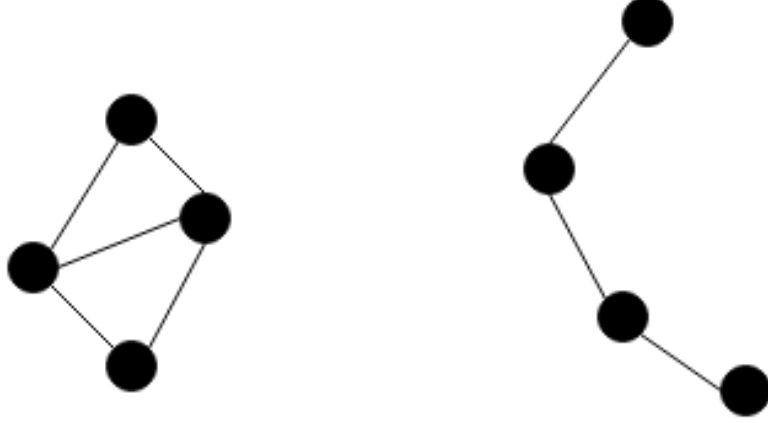


Figure 4.2: An example when two separate subnets formed

subnets unconnected. In this case, none of the gossip nodes are isolated but we still cannot successfully broadcast a message. Therefore, we applied Depth First Search (DFS) algorithm to ensure that all nodes in the network are connected in some way. Based on each gossip node's neighbor list, DFS would try to traverse all gossip nodes starting from any gossip node. If the algorithm is able to visit all gossip nodes, we consider this newly generated topology suitable for our simulation. On the other hand, when the algorithm cannot traverse all gossip nodes successfully, this simulation instance will be terminated.

As mentioned earlier, DFS algorithm need each gossip node's neighbors list in order to properly perform. To obtain this information, after the random gossip nodeplacement, the program can access each node's coordinates. Assuming node 1 ( $node_1$ ) has the coordinate of  $(x_1, y_1)$  and node 2 ( $node_2$ ) has the coordinate of  $(x_2, y_2)$ , the distance between  $node_1$  and  $node_2$  can be easily computed by the distance formula. Therefore, if we denote the distance between  $node_1$  and  $node_2$  is  $d$ , then  $d = \sqrt{(x_1 - x_2)^2 + (y_1 - y_2)^2}$ . Now if we denote each gossip node's WiFi range to be  $R$ , then  $node_1$  and  $node_2$  are neighbors when  $d \leq R$ . While  $node_1$  and  $node_2$  are not neighbors when  $d > R$ . We used this process to generate neighbors list for each gossip node. In practice, the global access of each gossip node's coordinate information is usually not easy to obtain. Thus, Hello packets are used to generate neighbors list for each gossip node.

The work flow of our simulation control program is described below.

- Read in simulation environment parameters.
- Create a source node and  $n$  gossip nodes.
- The wireless ad-hoc network channel speed is set to be 1Mbps for all gossip nodes.
- Create a special wireless ad-hoc network connection between a source node and a gossip node and set its speed to be 11Mbps.
- Compute the side size of a square area for nodes placement.
- Randomly place all nodes in the square area
- Install basic energy source and WiFi radio energy model on the gossip nodes.
- Assign IP addresses to all nodes.
- Install adaptive fanout gossip protocol and UDP client application on the gossip nodes.
- Install gossip generator application and UDP server application on the source node.
- Generate neighbors list for each gossip node.
- Check topology connectivity using DFS algorithm.
- If the topology is disconnected somehow, terminate this simulation.
- If the topology is connected, start the simulation.

The link speed among gossip nodes is set to be 1Mbps because it is sufficient to transmit a very small Data packet quickly. The link speed between the source node and one of the gossip node is set to be 11Mbps because we want to make sure that source node does not become the bottleneck for the performance of our proposed gossip protocol. Since all nodes including the source node are randomly placed in this area, we make sure that the WiFi range of the source node is large enough that it will always be able to reach any gossip nodes. The WiFi range of gossip nodes is set to be 50m in order to control node's degree.

As we stated earlier, the simulation will stop once any gossip node's energy is depleted. From that point, the program will enter the data collection and process stage. At this stage, the program is trying to calculate the following data:

- Message broadcast time (one output file per simulation)
- Average overhead per node per message (average within each simulation)
- Average energy consumption per node per message (average within each simulation)
- Network lifetime

For the message broadcast time, the program will access the vector stored in the source node that represent the time stamps for each generated new broadcast message. Similarly, it will also access  $n$  vectors from  $n$  gossip nodes. These vectors stored the received broadcast message time stamps of each gossip node. Let's take a look at an example where we have one source node and one gossip node and the protocol successfully broadcast  $m$  messages, if we denote the vector on the source node side to be  $T_s = \langle t_{s1}, t_{s2}, \dots, t_{sm} \rangle$  and the vector on the gossip node side to be  $T_g = \langle t_{g1}, t_{g2}, \dots, t_{gm} \rangle$ , then the delay for these messages are  $T_{delay} = T_g - T_s = \langle t_{g1} - t_{s1}, t_{g2} - t_{s2}, \dots, t_{gm} - t_{sm} \rangle$ . For the scenario where  $n$  gossip nodes participated in the broadcasting process, because we are interested in message broadcast time, the program will first calculate the  $T_{delay}$  for each gossip node ( $T_{delay_1}, T_{delay_2}, \dots, T_{delay_n}$ ). Then it will loop through the first element in those vectors and store the maximum delay because by our definition for one broadcast message the time difference between the last gossip node received the message and the time the source node generate that message is the broadcast time for that message. And then the program will repeat that process until it reaches the  $m_{th}$  broadcast message. However, we would like to point out that this process is only applied on a per simulation basis. To obtain the data that later our performance metrics need, further process need to be done.

For the overhead, we defined it as the total number of packets this protocol sent during the simulation. This includes Ack packet, Request packet, and Data packet. Our simulation control program first will access the *packetSent* counter on each gossip node. Then it will average over total number of broadcast messages ( $m$  messages). Finally, it

will take that number and average over number of gossip nodes ( $n$  gossip nodes). Again, this process is done in a per simulation basis. Further data process is needed to yield our desired performance metrics data.

Similar to the process of calculating average overhead per node per message, in order to compute average energy consumption per node per message, the program would first collect consumed energy from the gossip nodes, and then average over number of gossip nodes ( $n$ ). And finally it will take that number and average over total number of broadcast messages ( $m$ ).

The network lifetime is defined as the time duration which all gossip nodes have energy to receive and transmit packets. Therefore, the program simply output the simulation stop time to a file.



## Chapter 5: Performance Evaluation

In this chapter, we first will introduce our designed performance metrics in order to properly evaluate our proposed adaptive fanout push-pull gossip protocol. Then we will explain our simulation environment settings. Finally, we will analyze the simulation results.

### 5.1 Performance Metrics

As we stated in Section 3.1.1, the objective of our proposed approach is to achieve the balance between fast broadcasting time and long network lifetime. So obviously, the first two performance metrics that we proposed are *Average Network Lifetime* and *Average Message Broadcast Time*. Other performance metrics are *Average Overhead Per Node Per Message*, *Average Consumed Energy Per Node Per Message*, and *Average Number of Success Broadcast Messages*.

#### 5.1.1 Average Network Lifetime

Before we define *Average Network Lifetime*, we need to define *Network Lifetime* first.

**Network Lifetime:** The time duration which a wireless ad-hoc network can physically broadcast messages successfully.

When a gossip node's energy is depleted, this gossip node will no longer be able to transmit or receive new broadcast messages. Thus, this network is considered to be physically unable to broadcast messages successfully. Now the definition of *Average Network Lifetime* is simply just an average over all *Network Lifetime* under  $n$  gossip nodes case. For example, if we ran  $s$  simulations under  $n = 10$  setting, and we denote *Average Network Lifetime* for 10 gossip nodes as  $L_{avg\_10}$ , then the following equation can be used to calculate the *Average Network Lifetime*.

$$L_{avg\_10} = \frac{L_1 + L_2 + \dots + L_s}{s}$$

This performance metric measures how long a wireless ad-hoc network with  $n$  gossip nodes can stay connected when running our proposed adaptive fanout gossip protocol.

### 5.1.2 Average Message Broadcast Time

Before we jump into the definition of *Average Message Broadcast Time*, we first need to clearly define *Message Broadcast Time*.

**Message Broadcast Time:** The maximum delay among gossip nodes for each broadcast message.

Because here we are trying to measure the broadcast time of a certain message, it only makes sense when we sample the maximum delay among all gossip nodes because the message received time of the last gossip node determined our message broadcast time for a particular message. Now the *Average Message Broadcast Time* is just an average over all message broadcast time under  $n$  gossip node case. Now because the randomness of our proposed gossip protocol, each simulation under  $n$  gossip node case can result in different number of success broadcast messages. Therefore, for  $n$  gossip node case simulations, we first calculate the *Average message broadcast time* for each simulation. And then we perform the average among those number to obtain this performance metrics data.

For example, let's denote the *Average Message Broadcast Time* for  $i$ th simulation as  $T_i$  and the *Average Message Broadcast Time* for  $n$  nodes as  $T_{avg-n}$ . If we performed  $s$  simulations, then the following equation can be used to calculate this metric:

$$T_{avg-n} = \frac{T_1 + T_2 + \dots + T_s}{s}$$

This metric indicates the time needed for a broadcast message to reach every gossip node in the network.

### 5.1.3 Average Overhead Per Node Per Message

The *overhead* here is defined as the total number of packets sent by a gossip node. These packets includes Ack packet, Request packet, and Data packet. For every simulation, in order to accurately measure the overhead for each gossip node and for each broadcast message, we simply performed an average over  $n$ . And then take that number and

further average over number of broadcast messages being sent. So for  $k$ th simulation, if we denote the overhead of node  $i$  for message  $j$  as  $O_{ij}$ , the number of gossip nodes are  $n$ , and the system broadcast  $m$  messages. Then for this simulation, the *Average Overhead Per Node Per Message* can be computed using the following equation:

$$O_k = \frac{(O_{11} + O_{21} + \dots + O_{n1}) + \dots + (O_{1m} + O_{2m} + \dots + O_{nm})}{n \times m}$$

If we performed  $s$  simulations under  $n$  gossip nodes setting, then the *Average Overhead Per Node Per Message* among these simulations is:

$$O_{avg-n} = \frac{O_1 + O_2 + \dots + O_s}{s}$$

This performance metric indicates how many packets are sent out for a gossip node to facilitate broadcasting one message.

#### 5.1.4 Average Energy Consumption Per Node Per Message

This performance metric is quite self-explanatory. We measure the amount of energy consumed by each gossip node during the simulation. Then we take that number and average among  $m$  messages.  $E_k$  is the *Average Energy Consumption Per Node Per Message* for the  $k$ th simulation under  $n$  gossip nodes.

$$E_k = \frac{E_{node\_1} + E_{node\_2} + \dots + E_{node\_n}}{n \times m}$$

Now if we ran  $s$  simulations, then *Average Energy Consumption Per Node Per Message* under  $n$  gossip nodes can be calculated using the following equation:

$$E_{avg-n} = \frac{E_1 + E_2 + \dots + E_s}{s}$$

This metric measures the amount of energy needed for a gossip node to facilitate broadcasting one message.

### 5.1.5 Average Number of Broadcast Messages

This metric measures how many messages can be successfully broadcast with limited energy sources. If we ran  $s$  simulations under  $n$  gossip nodes setting, this metric can be computed using the following equation:

$$N_{avg\_n} = \frac{N_1 + N_2 + \dots + N_s}{s}$$

## 5.2 Simulation Environment Settings

In order to properly evaluate our proposed push-pull gossip protocol, we need to compare it to the same basic push-pull gossip protocol but with constant *Fanout* settings. Here we picked three typical *Fanout* values. They are  $f = 1, 5, 10$ . By obtaining performance metrics data from these three constant fanout settings, we can study how different *Fanout* affect protocol performance.

The simulation environment setting is summarized below.

- Fanout: 1, 5, 10, or adaptive
- Number of nodes: 10, 50, 90, 130, 170
- WiFi speed among gossip nodes: 1Mbps
- WiFi speed between the source node and a gossip node: 11Mbps
- MAC: IEEE 802.11 for gossip nodes and source node
- RTS/CTS: On
- Gossip node maximum WiFi range: 50m
- Source node maximum WiFi range: 500m
- Simulation stop time: 100000.0s
- Initial battery energy: 108.0J (3V)
- Gossip interval: 1.0s

- Request interval 5.0s
- WiFi radio idle current: 0.0A
- WiFi radio sleep current: 0.0A
- WiFi radio transmit current: 0.38A
- WiFi radio receive current: 0.313A
- Gossip nodes IP address: 10.1.1.0/24
- Source node and a gossip node's IP address: 10.1.2.0/24

As we stated earlier, the simulation stop time is set to be large enough so that the energy sources on gossip nodes will be depleted first. Thus, it will trigger the termination of our simulations.

### 5.3 Result Analysis

In order to obtain simulation data for these settings, we ran 2000 simulations. Because of the random placement of gossip nodes can potentially generate a disconnected topology, some of the simulations will be terminated in the beginning. Table 5.1 shows the number of successful simulations under each number of gossip nodes setting. It is worth noting that this table holds true for all four *Fanout* settings.

Table 5.1: Number of Simulations Run

Number of gossip nodes	Total number of simulations	Number of success simulations
10	100	85
50	100	52
90	100	50
130	100	46
170	100	34

By conducting statistical analysis based on the method in Section 5.1, we were able to extract the data of each performance metrics.

Figure 5.1 depicts the *Average Message Broadcast Time* over number of gossip nodes. As we would expect, under any *Fanout* setting, the *Average Message Broadcast Time*

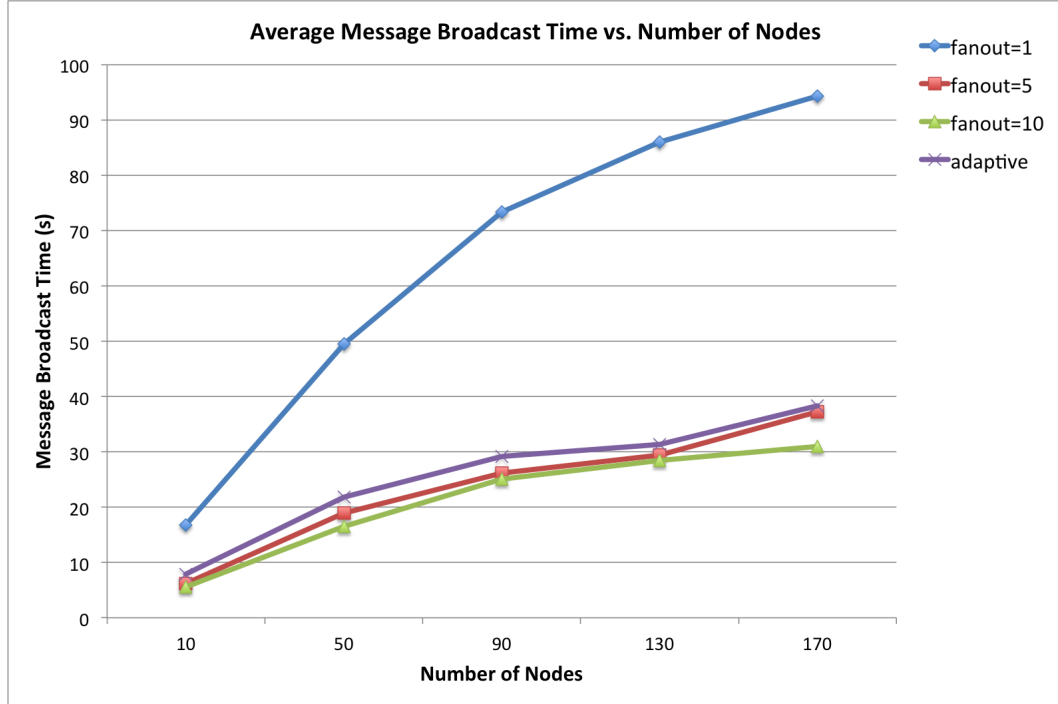


Figure 5.1: Average message broadcast time vs. number of nodes

will increase as the number of gossip nodes increase. It is especially obvious for  $f = 1$  setting. For other *Fanout* settings, their *Average Message Broadcast Time* are much shorter than  $f = 1$  setting across different number of gossip nodes settings. We can see a huge performance improvement when *Fanout* is switched from 1 to 5. That is because a gossip node can forward the broadcast message to more neighbors comparing to  $f = 1$  setting. However, the performance improvement from  $f = 5$  to  $f = 10$  is marginal. We believe that it is related to the average node's degree since a *Fanout* setting that exceeds the number of neighbors a gossip node has will bring no additional performance boost. Our adaptive fanout approach performed as good as  $f = 5$  setting even though its *Fanout* is ranging from 1 to 5 during a simulation.

Figure 5.2 presents the *Average Network Lifetime* over different number of gossip nodes. For three constant *Fanout* settings, the *Average Network Lifetime* decreases as *Fanout* increases. This is within our expectation because for every gossip round, a gossip node with a higher *Fanout* setting will have to contact more neighbors thus consume

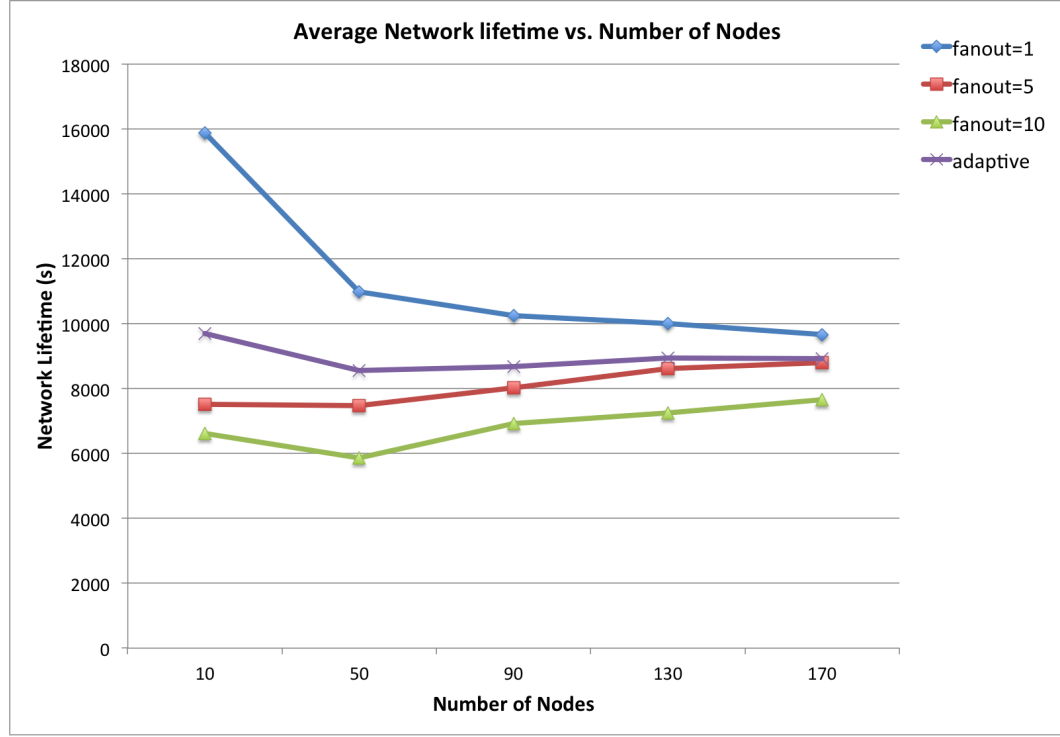


Figure 5.2: Average network lifetime vs. number of nodes

more energy.  $f = 1$  setting has the best *Average Network Lifetime* but as we see in Figure 5.1, it has the worst *Average Message Broadcast Time*. Under  $f = 5$  setting, the *Average Network Lifetime* is reasonably good while the *Average Message Broadcast Time* is shorter. However, our proposed adaptive fanout setting can achieve even better *Average Network Lifetime* comparing to  $f = 5, 10$  settings while still perform as good as the other two in terms of *Average Message Broadcast Time*.

From Figure 5.3, we can see that as number of gossip nodes increases, the *Average Energy Consumption Per Node Per Message* increases as expected. For the ease of discussion, in the following chapter we will call it *Average Energy Consumption*. The interesting part here we would like to point out is that  $f = 1$  setting actually has the highest energy consumption. The reason is that even though it has the longest *Average Network Lifetime*, it also has the worst *Average Message Broadcast Time*. So given these two constrains, the number of messages it can broadcast is less than other *Fanout*

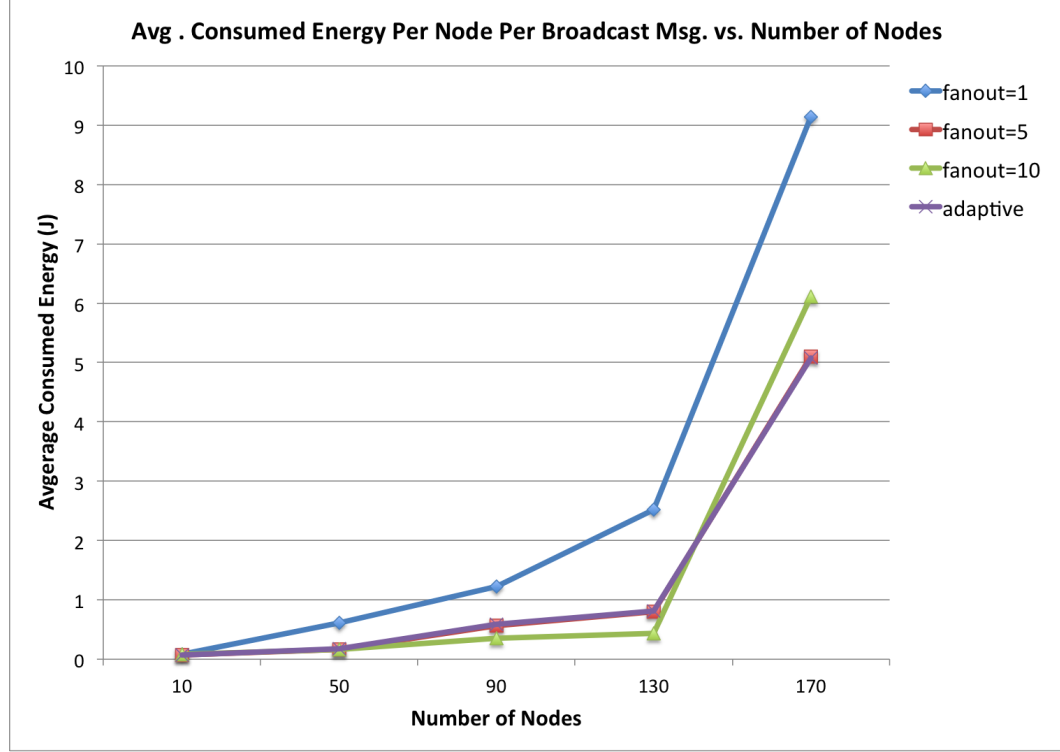


Figure 5.3: Average consumed energy per node per message vs. number of nodes

settings. Since we computed this metric on a per message basis, it would result in a higher *Average Energy Consumption*. Under  $f = 5$  and adaptive fanout setting, their *Average Energy Consumption* plots are almost overlapping each other. The reason is the trade off between *Average Message Broadcast Time* and *Average Network Lifetime*.  $f = 10$  setting has the lowest *Average Energy Consumption* except for 170 gossip nodes setting, but as shown in Figure 5.2, it has the worst *Average Network Lifetime*.

Figure 5.4 shows the results of *Average Overhead Per Node Per Message* over various number of gossip nodes. For the ease of discussion, from now on we will call it *Average Overhead*. Comparing Figure 5.4 to Figure 5.3, we can see that the shape of each plot is almost identical even though the unit on the y-axis is different. That is because energy consumption is closely related to overhead since overhead is defined as the number of packets sent by each gossip node. Therefore, the same analysis on Figure 5.3 can be applied here as well.



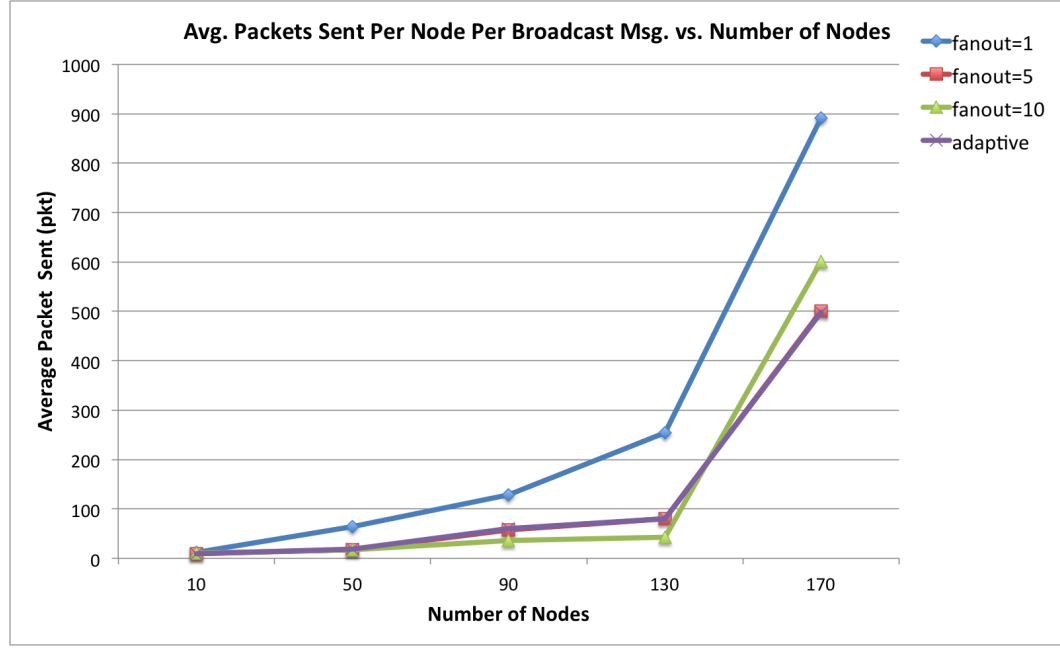


Figure 5.4: Average overhead per node per message vs. number of nodes

Lastly, Figure 5.5 presents the number of messages broadcast over different number of gossip nodes.  $f = 1$  setting can deliver the least amount of messages comparing to other *Fanout* settings. In general, higher *Fanout* setting will increase the number of messages the protocol can deliver. However, as we see in Figure 5.1, switching *Fanout* from 5 to 10 would result in a very limited performance boost. Our proposed adaptive fanout approach performed as good as  $f = 5, 10$  setting while as shown in Figure 5.2 it has longer *Average Network Lifetime*.

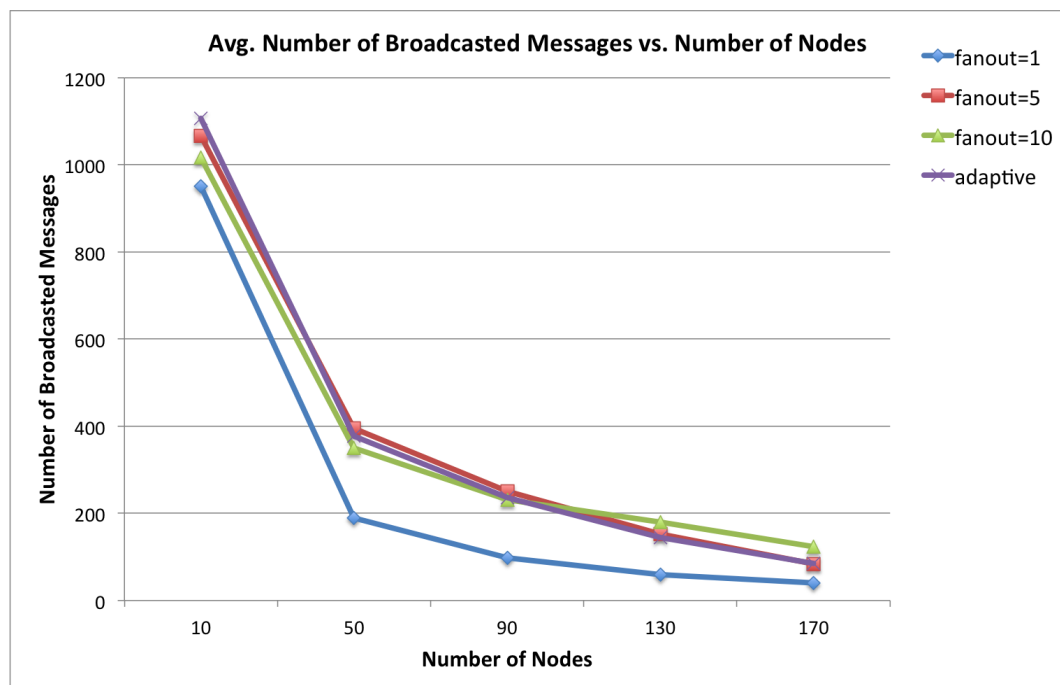


Figure 5.5: Average number of broadcast messages vs. number of nodes

## Chapter 6: Conclusions and Future Work

In this thesis, we introduced research progress in gossip techniques for wireless broadcasting in recently years. We pointed out that despite all these efforts dedicated into reducing gossip broadcasting protocol overhead, very little research has focused on energy efficiency and network lifetime. Those aspect used to be not very important when designing new broadcasting protocols because nodes usually have stable power. However, with the emergence of Internet of Things (IoT) devices, broadcasting protocols that take energy consumption into account and optimizing it will be favored over those that do not. Based on our observation of the tradeoff between battery life and broadcasting time regarding *Fanout* parameter, we proposed a new energy-aware gossip broadcasting protocol that could balance between network lifetime and broadcasting time. In order to evaluate the performance of our proposed approach, we designed several metrics and we developed the protocol in open-source software ns-3. Simulation results showed that comparing to constant  $f = 5$  setting, our adaptive approach significantly extended network lifetime while only performed slightly slower in term of message broadcasting time. We suspect the casue for marginal performance improvements for  $f = 10$  setting comparing to  $f = 5$  setting is the average node's degree. In other words, very little performance boost can be observed when *Fanout* is set beyond average node's degree since a node simply cannot reach out to 10 neighbors when it only has 5 neighbors. As we discussed earlier,  $f = 1$  setting has the worst message broadcasting time. But on the flip side, it would result in a longest network lifetime which could be desirable for some applications.

In conclusion, our proposed energy-aware adaptive gossip broadcasting protocol can leverage the advantages of low *Fanout* setting and high *Fanout* setting. Thus, we can extend network lifetime while still perform as good as high *Fanout* setting in term of broadcasting time. Constant  $f = 1$  setting is recommended for networks that consists of nodes with strict energy constrain.

For future work, we would like to use multicast instead of multiple unicast for each node to send the new message. The reason is that if we assume  $XJ$  is the amount

of energy used to transmit a packet for a sender, and  $f = 5$ , one multicast will only consum  $XJ$  while five unicast will consum  $5XJ$ . Another interesting scenerio would be to set very different initial energy but same battery capacity for each node. Thus each node would be operating at different *Fanout* setting from the begining due to different remaining energy fraction. We believe this would better capture the advantage of our proposed appraoch over constant *Fanout* setting.

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