Fuzzy Optimization for Mobile Ad Hoc Networks: a Bottom-up Cross-layer Approach

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Abstract

In this paper, we introduce a new method for cross-layer design in mobile ad hoc networks. We use fuzzy logic system (FLS) to coordinate physical layer, data-link layer and application layer for cross-layer design. Ground speed, average delay and packets successful transmission ratio are selected as antecedents for the FLS. The output of FLS provides adjusting factors for the AMC (Adaptive Modulation and Coding), transmission power, retransmission times and rate control decision. Simulation results show that our cross-layer design can reduce the average delay, increase the throughput and extend the network lifetime. The network performance parameters could also keep stable after the cross-layer optimization.

Keywords: Cross-layer Design, Fuzzy Logic System, Ad Hoc, Network Performance, Mobile.

1. INTRODUCTION

The demand for energy efficiency and Quality of Service (QoS) in mobile ad hoc networks is growing in a rapid speed. To enhance the energy efficiency and QoS, we consider the combination of physical layer, data-link layer and application layer together, a cross-layer approach. A strict layered design is not flexible enough to cope with the dynamics of the mobile ad hoc networks [1]. Cross-layer design could introduce the layer interdependencies to optimized overall network performance. The general methodology of cross-layer design is to maintain the layered architecture, capture the important information that influence other layers, exchange the information between layers and implement adaptive protocols and algorithms at each layer to optimize the performance.

Lots of previous works have focused on cross-layer design for QoS provision. Liu [2] combine the AMC at physical layer and ARQ at the data link layer. Ahn [3] use the info from MAC layer to do rate control at network layer for supporting real-time and best effort traffic. Akan [4] propose a new adaptive transport layer suite including adaptive transport protocol and adaptive rate control protocol based on the lower layer information.

Some works related to energy efficiency have been reported. Banbos proposes a power-controlled multiple access schemes in [5]. This protocol reveals the trade-off of the transmitter power cost and backlog/delay cost in power control schemes. Zhu [6] proposes a minimum energy routing scheme, which consider the energy consumption for data packets as well as control packets of routing and multiple access. In [7], Sichitiu proposes a cross-layer scheduling method. Through combining network layer and MAC layer, a deterministic, schedule-based energy conservation scheme is proposed. This scheme drives its power efficiency from eliminating idle listening and collisions.

However, cross-layer design can produce unintended interactions among protocols, such as an adaptation loops. It is hard to characterize the interaction at different layers and joint optimization across layers may lead to complex algorithm.

Our algorithm is quite different from all the previous works. We propose to use the Fuzzy Logic System (FLS) in the cross-layer design. We define a coherent time, a certain period of time. During this coherent time, the AMC (Adaptive Modulation and Coding), transmission power, retransmission times and rate control decision are used for packet transmission. After this time, we adaptively adjust these parameters by FLS again basing on current ground speed, average delay and the packets successful transmission ratio.

By applying the FLS mechanism to the cross-layer, a better QOS provision and energy efficiency are achieved.

The remainder of this paper is structured as following. In section 2, we introduce the preliminaries. In section 3, we make a overview of fuzzy logic systems. In section 4, we apply the FLS into the cross-layer design. Simulation results and discussions are presented in section 5. In section 6, we conclude the paper.

2. PRELIMINARIES

1. IEEE 802.11a OFDM PHY

The physical layer is the interface between the wireless medium and the MAC [8]. The principle of OFDM is to divide a high-speed binary signal to be transmitted over a number of low data-rate subcarriers. A key feature of the IEEE 802.11a PHY is to provide 8 PHY modes with different modulation schemes and coding rates, making the idea of link adaptation feasible and important, as listed in Table 1. BPSK, QPSK, 16-QAM and 64-QAM are the supported modulation schemes. The OFDM provides a data transmission rates from 6 to 54MBPS. The higher code rates of 2/3 and 3/4 are obtained by puncturing the original rate 1/2 code.

Mode	Modulation	Code Rate	Data Rate	Bps
1	BPSK	1/2	6Mbps	3
2	BPSK	3/4	9Mbps	4.5
3	QPSK	1/2	12Mbps	6
4	QPSK	3/4	18Mbps	9
5	16-QAM	1/2	24Mbps	12
6	16-QAM	3/4	36Mbps	18
7	64-QAM	2/3	48Mbps	24
8	64-QAM	3/4	54Mbps	27

TABLE 1: Eight PHY Modes of the IEEE802.11A PHY

2. IEEE 802.11 MAC

The 802.11 MAC uses Carrier-Sense Multiple Access with Collision Avoidance (CSMA/CA) to achieve automatic medium sharing between compatible stations. In CSMA/CA, a station senses the wireless medium to determine if it is idle before it starts transmission. If the medium appears to be idle, the transmission may proceed, else the station will wait until the end of the in-progress transmission. A station will ensure that the medium has been idle for the specified inter-frame interval before attempting to transmit.

Besides carrier sense and RTS/CTS mechanism, an acknowledgment (ACK) frame will be sent by the receiver upon successful reception of a data frame. Only after receiving an ACK frame correctly, the transmitter assumes successful delivery of the corresponding data frame. The sequence for a data transmission is: RTS-CTS-DATA-ACK.

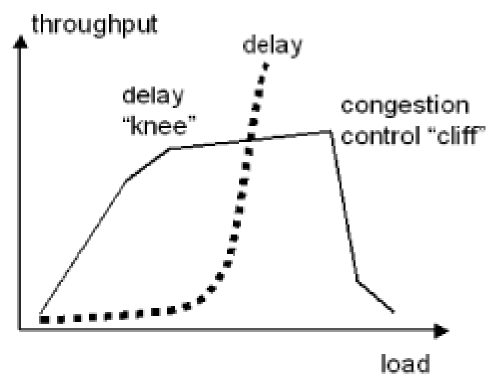
A mobile node will retransmit the data packet when finding failing transmission. Retransmission of a signal packet can achieve a certain probability of delivery. There is a relationship between the probability of delivery p and retransmission times n:

$$n = 1.45 \ln \frac{1}{1-p}$$

The IEEE 802.11 standard requires that the transmitter's MAC discard a data frame after certain number of unsuccessful transmission attempts. According to the requirement of probability of delivery, we choose the minimum number of retransmission. The advantage is we can save energy through avoiding unnecessary retransmission, and ensure probability of delivery.

3. Application Layer

Traffic in application layer is divides into two classes: real-time and best-effort. Each node in the mobile ad hoc networks independently regulates best effort traffic. It is proposed to control the rate of the best-effort traffic to avoid excessive delays of the real-time traffic by using local per-hop delays as a feedback to local rate controller [3]. The general behavior of a congestion-controlled system is illustrated in Fig.1. The control algorithm ensures that the system operates around, or preferably close to the "cliff", which ensure maximum system throughput, but at the cost of large average packets delay. The control algorithm discussed, one the other hand, keep the system at the delay "knee" where the system throughput is almost the same as the at the cliff, but the buffers are significantly less loaded, so the delay is close the minimum. Due to loss typically happens at the cliff, while delays start to increase at the knee, we use the per-hop MAC delay as a feedback for local control instead of the packet loss.



Error! Not a valid link.

FIGURE 1: General Behavior of a Congestion-controlled System

When MAC layer acquires access to the channel, the nodes will exchange the RTS-CTS-DATA-ACK packets. After the transmitters receive an ACK packet, a packet is transmitted successfully. The packet delay represents the time it took to send the packet between the transmitter and the next-hop receiver, including the deferred time and the time to fully acknowledge the packet. In this paper, we assume that there will be always best-effort traffic present that can be locally and rapidly rate controlled in an independent manner at each node to yield necessary low delays and stable throughputs.

4. Energy

A mobile node consumes significant energy when it transmits or receives a packet. But we will not consider the energy consumed when the mobile node is idle.

The distances between two nodes are variable in the mobile ad hoc networks and the power loss model is used. To send the packet, the sender consumes [9],

$$P_{tx} = P_{elec} + \varepsilon_{fs} \cdot d^2$$

and to receive the packet, the receiver consumes,

$$P_{rx} = P_{elec}$$

where P_{elec} represents the power that is necessary for digital processing, modulation, and ε_{fs} represents the power dissipated in the amplifier for the free space distance d transmission.

A joint characteristic of most application scenarios of mobile ad hoc networks is that mobile nodes only have a limited energy supply which might not even be rechargeable, hence they have to be energy-efficient as possible. Transmitter power control allows interfering communication links sharing the same channel to achieve their required QoS levels, minimizing the needed power, mitigating the channel interference, and maximizing the network user/link capacity.

5. Delay

The packet transmission delay between the mobile nodes includes three parts: the wireless channel transmission delay, the Physical/MAC layer transmission delay, and the queuing delay[10]

Defining D as the distance between two nodes and C as the light speed, the wireless channel transmission delay as:

$$Delay_{-ch} = \frac{D}{C}$$

The Physical/MAC layer transmission delay will be decided by interaction of the transmitter and the receive channel, the node density and the node traffic intensity etc.

The queuing delay is decided by the mobile node I/O system-processing rate, the subqueue length in the node.

In order to make the system ``stable'', the rate at which node transfers packets intended for its destination must satisfy all nodes that the queuing lengths will not be infinite and the average delays will be bounded

6. Node Mobility and Channel Fading

Mobility of a mobile node generates a doppler shift, which is a key parameter of fading channel. The doppler shift is

$$f_d = \frac{v}{c} f_c$$

Where v is the ground speed of a mobile node, c is the speed of light ($3 \times 10^8 m/s$), and f_c is the carrier. In our simulation, we used the carrier is 6GHz. For reference, if a node moves with speed 10 m/s, the doppler shift is 200Hz.

We model channel fading in ad hoc networks as Rician fading. Rician fading occurs when there is a strong specular (direct path or line of sight component) signal in addition to the scatter (multipath) components. For example, in communication between two infraed sensors, there exists a direct path. The channel gain,

$$g(t) = g_I(t) + jg_Q(t)$$

can be treated as a wide-sense stationary complex Gaussian random process, and $g_I(t)$ and $g_Q(t)$ are Gaussian random processes with non-zero means $m_I(t)$ and $m_Q(t)$ respectively; and they have same variance σ_g^2, then the magnitude of the received complex envelop has a Rician distribution,

$$p_\alpha(x) = \frac{x}{\sigma^2}\exp\{-\frac{x^2+s^2}{2\sigma^2}\}I_0(\frac{xs}{\sigma^2}) \quad x \ge 0$$

Where $s^2 = m_I^2(t) + m_Q^2(t)$ and $I_0(\cdot)$ is the zero order modified Bessel function. This kind of channel is known as Rician fading channel. A Rician channel is characterized by two parameters, Rician factor K, which is the ratio of the direct path power to that of the multipath, i.e., $K = s^2/2\sigma^2$, and the Doppler spread (or single-sided fading bandwidth) f_d. We simulate the Rician fading using a direct path added by a Rayleigh fading generator. The Rayleigh fade generator is based on Jakes' model[11] in which an ensemble of sinusoidal waveforms are added together to simulate the coherent sum of scattered rays with Doppler spread f_d arriving from different directions to the receiver. The amplitude of the Rayleigh fade generator is controlled by the Rician factor K. BPSK, QPSK, 16-QAM and 64-QAM are the supported modulation schemes for IEEE 802.11a OFDM physical layer. We can show their performance curves with Rician fading in Fig. 2.

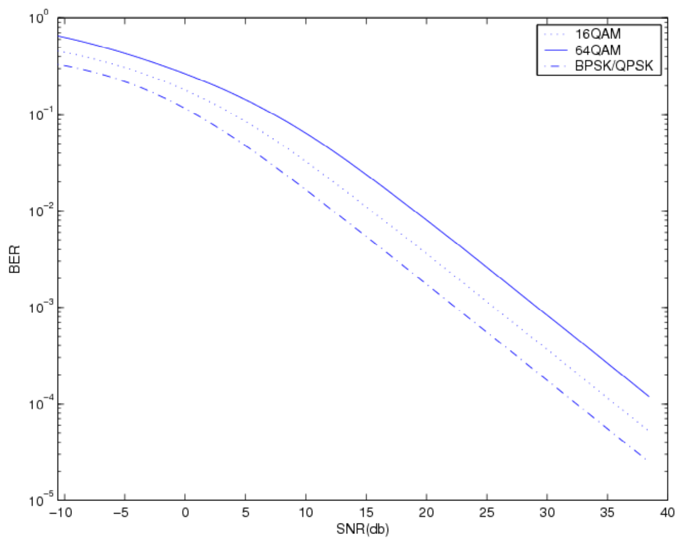


FIGURE 2: Modulation Curves with Rician Fading

After we introduce the channel coding and node mobility into the modulation schemes, the modulation curves will change a lot. For the same SNR, channel coding will improve the BER performance and the mobility will degrade the BER performance.

7. One-step Markov Path Model

The mobile nodes are roaming independently with variable ground speed. The mobility model is called one-step Markov path model [12]. The probability of moving in the same direction as the previous move is higher than other directions in this model, which means this model has memory. Fig.3 shows the probability of the six directions.

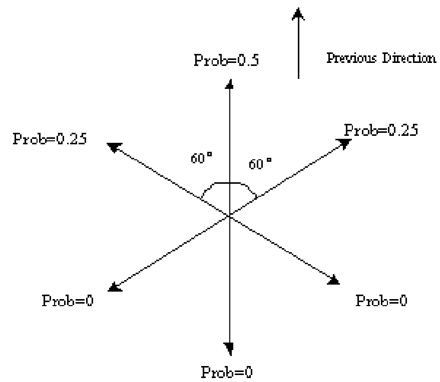


FIGURE 3: One-step Markov Path Model

3. OVERVIEW OF FUZZY LOGIC SYSTEMS

Fig. 4 shows the structure of a fuzzy logic system (FLS).

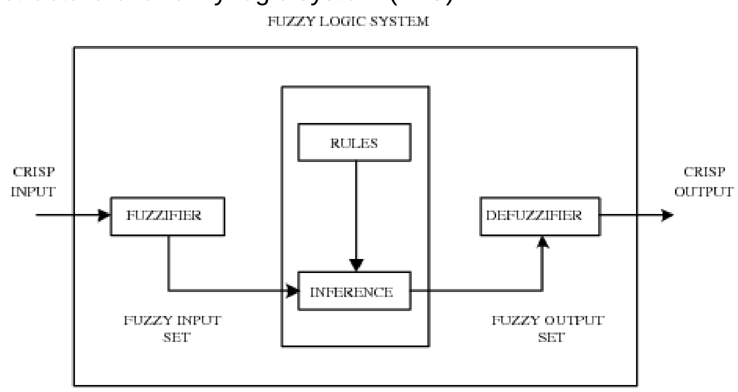


FIGURE 4: The structure of a fuzzy logic system

When an input is applied to a FLS, the inference engine computes the output set corresponding to each rule. The defuzzifer then computes a crisp output from these rule output sets [13].

Consider a p-input 1-output FLS, using singleton fuzzification center-of-sets, defuzzification[14] and ``IF-THEN'' rules of the form[15].

R^l: IF x_1 is F_1^l and x_2 is F_2^l and … and x_p is F_p^l, THEN y is G^l.

Assuming singleton fuzzification, when an input $X' = \{x_1', \cdots, x_p'\}$ is applied, the degree of firing corresponding to the lth rule is computed as

$$\mu_{F_1^l}(x_1') * \mu_{F_2^l}(x_2') * \cdots * \mu_{F_p^{l'}}(x_p') = \Gamma_{i=1}^{p} \mu_{F_i^l}(x_i')$$

where $*$ and both indicate the chosen t-norm. There are many kinds of defuzzifiers. In this paper, we focus, for illustrative purposes, on the center-of-sets defuzzifier. It computes a crisp output for the FLS by first computing the centroid, c_G^l, of every consequent set G^l, and, then computing a weighted average of these centroids. The weight corresponding to the lth rule consequent centroid is the degree of firing associated with the lth rule, $\Gamma_{i=1}^{p} \mu F_i^l(x_i')$, so that

$$y_{\cos}(x^{'}) = \frac{\Sigma_{l=1}^{M} c_{G^l} \Gamma_{i=1}^{p} \mu_{F_i^l}(x_i^l)}{\Sigma_{i=1}^{M} \Gamma_{i=1}^{p} \mu_{F_i^l}(x_i^{'})}$$

where M is the number of rules in the FLS.

4. FUZZY APPLICATION FOR CROSS-LAYER DESIGN

AMC, transmission power, retransmission times and rate control decision will manage the energy consumption and QoS provision. How to choose a proper adjusting factor for these parameters will determine the wireless ad hoc networks performance.

We collect the knowledge for adjusting factor selection based on the following three antecedents:

1) Antecedent 1. Ground speed.
2) Antecedent 2. Average delay.
3) Antecedent 3. Packets successful transmission ratio.

The linguistic variables used to represent the Ground speed, average delay and packets successful transmission ratio were divided into three levels: *low, moderate, and high.* The consequents -- the adjusting factor for the AMC, transmission power, retransmission times and rate control decision were divided into 9 levels, *decrease one, decrease two, decrease three, decrease four, unchanged, increase one, increase two, increase three and increase four*. Fig.5 shows the FLS application for the cross-layer design.

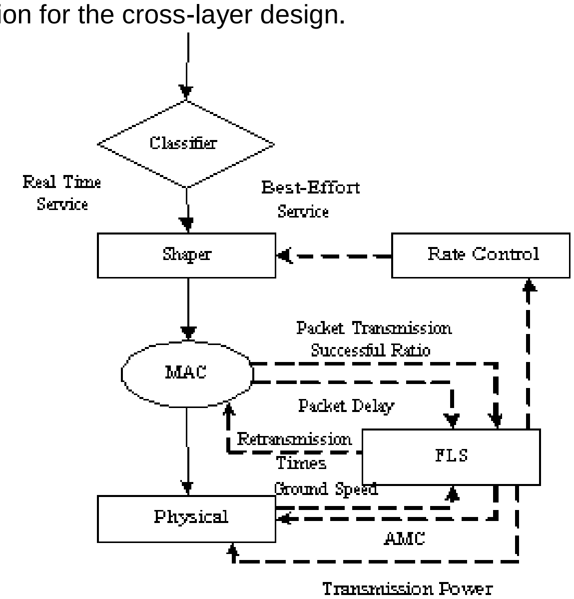


FIGURE 5: Cross-layer Design Algorithm

We designed questions such as: IF *ground speed* is *low*, *average delay* is *low* and *packets successful transmission ratio* is *high*, THEN *the adjusting factor* is ________

So we need to set up $3^3 = 27$ (because every antecedent has 3 fuzzy sub-sets, and there are 3 antecedents) rules for this FLS. We summarized these rules in Table 2. Antecedent1 is its ground speed, Antecedent 2 is its average delay, and Antecedent 3 is its packet transmission ratio. Consequent 1 is adjusting factor for retransmission times, Consequents is the adjusting factor for AMC, Consequent 3 is adjusting factor for transmission power, and Consequent 4 is adjusting factor for rate control decision.

R #	A 1	A 2	A 3	C1	C2	C3	C4
1	low	low	low	Increase two	Decrease two	unchanged	unchanged
2	low	low	moderate	unchanged	unchanged	Decrease two	Decrease two
3	low	low	high	Decrease two	Increase two	Decrease four	Decrease four
4	low	moderate	low	Increase one	Decrease one	Increase one	Increase one
5	low	moderate	moderate	Decrease one	increase one	Decrease one	Decrease one
6	low	moderate	high	Decrease three	Increase three	Decrease three	Decrease three
7	low	high	low	unchanged	unchanged	Increase two	Increase two
8	low	high	moderate	Decrease two	Increase two	unchanged	unchanged
9	low	high	high	Decrease four	Increase four	Decrease two	Decrease two
10	moderate	low	low	Increase three	Decrease three	Increase one	Increase one
11	moderate	low	moderate	Increase one	Decrease one	Decrease one	Decrease one
12	moderate	low	high	Decrease one	Increase one	decrease three	Decrease three
13	moderate	moderate	low	Increase two	Decrease two	Increase two	Increase two
14	moderate	moderate	moderate	unchanged	unchanged	unchanged	unchanged
15	moderate	moderate	high	Decrease two	Increase one	Decrease two	Decrease two
16	moderate	high	low	Increase one	Decrease one	Increase three	Increase three
17	moderate	high	moderate	Decrease one	Increase one	Increase one	Increase one
18	moderate	high	high	Decrease three	Increase three	Decrease one	Decrease one
19	high	low	low	Increase two	Decrease four	Increase one	Decrease one
20	high	low	moderate	Increase two	Decrease two	unchanged	unchanged
21	high	low	high	unchanged	unchanged	Decrease two	Decrease two
22	high	moderate	low	Increase three	Decrease three	Increase three	Increase three
23	high	moderate	moderate	Increase one	Decrease one	Increase one	Increase one
24	high	moderate	high	Decrease one	Increase one	Decrease one	Decrease one
25	high	high	low	Increase two	Decrease two	Increase four	Increase four
26	high	high	moderate	unchanged	unchanged	Increase two	Increase two
27	high	high	high	Decrease two	Increase two	unchanged	unchanged

TABLE 2: The fuzzy rules for cross-layer design

We used trapezoidal membership functions (MFs) to represent *low, high, increase four* and *decrease four*, and triangle MFs to represent *moderate, unchanged, increase one, increase two, increase three, decrease one, decrease two* and decrease *three*.

We show these MFs in Fig.6 and Fig.7.

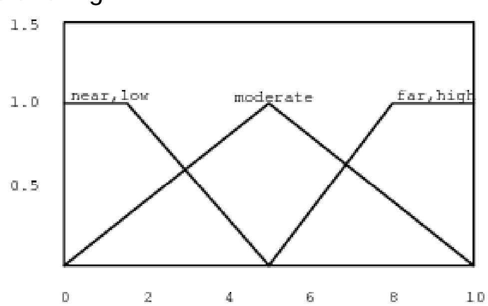


FIGURE 6: MFs for Antecedents

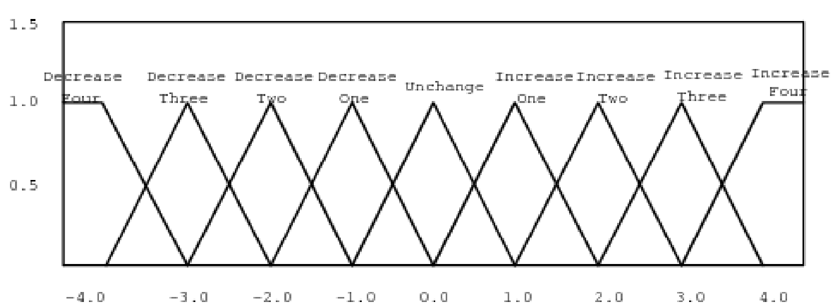


FIGURE 7: MFs for Consequents

In our approach to form a rule base, we chose a single consequent for each rule. We design a fuzzy logic system using rules such as:

R^l: IF ground speed (x_1) is F_l^1, average delay (x_2) is F_l^2, and packet successful transmission ratio (x_3) is F_l^3, For every input (x_1, x_2, x_3), the output is computed using

For every input ($(x_{1,} x_{2,} x_3)$, the output is computed using

$$y(x_1, x_2, x_3) = \frac{\Sigma_{l=1}^{27} \mu_{F_l^1}(x_1)\mu_{F_l^2}(x_2)\mu_{F_l^3}(x_3)c_G^l}{\Sigma_{l=1}^{27} \mu_{F_l^1}(x_1)\mu_{F_2^2}(x_2)\mu_{F_l^3}(x_3)}$$

We compute the adjusting factors and adjust the network parameters dynamically. Comparing to the constant parameters, the fuzzy optimization for cross-layer design can meet QoS and energy requirement.

5. SIMULATIONS

We implemented the simulation model using the OPNET modeler. The simulation region is 300×300 meters. There were 12 mobile nodes in the simulation model, and the nodes were roaming independently with variable ground speed between 0 to 10 meters per second. The mobility model was called one-step Markov path model. The movement would change the distance between mobile nodes.

1. Average Delay

Because data communications in the mobile networks had trimming constraints, it was important to design the network algorithm to meet a kind of end-end deadline [16]. We used the average delay to evaluate the network performance.

$$d_{avergage} = \frac{\sum_{i=1}^{k} d_i}{k}$$

Each packet was labeled a timestamp when the source mobile node generated it. When its destination mobile node received it, the time interval was the transmission delay.

Fig.8 showed the delay performance of the constant parameters and the one after cross-layer optimization for the real time traffic, the best effort traffic and all the traffic. Cross-layer optimization made a tradeoff for the average delay between the real time traffic and the best effort traffic. For the real time traffic, the cross-layer optimization would enlarge about 0.6 seconds. However for the best effort case, the cross-layer optimization could reduce the delay by up to 90.53%. For the all traffic, the cross-layer optimization could reduce the delay by up to 71.85%, which meant the cross-layer optimization could improve the average delay performance for the whole system. As showed in the best effort case, the cross-layer optimization could make the average delay "stable", which was important for the communication system design.

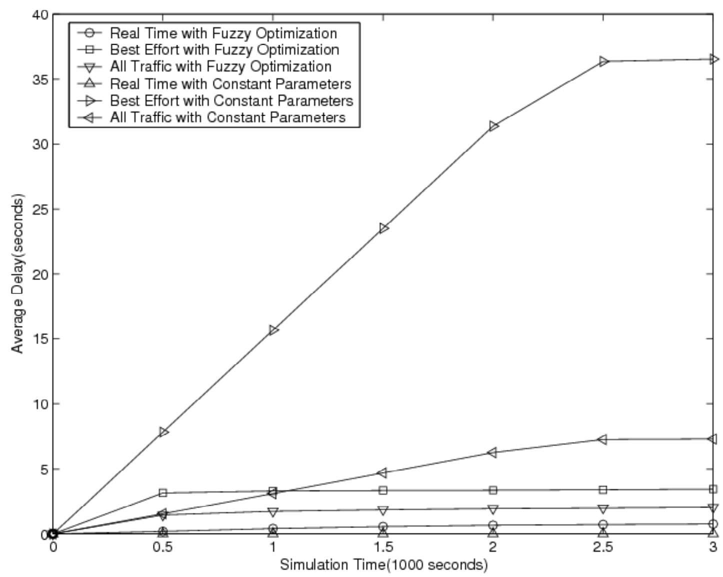


FIGURE 8: Average Delay

2. Energy Efficiency

It was not convenient to recharge the battery, so the energy efficiency was extremely important for mobile ad hoc networks. The network should keep an enough number of ``live'' mobile nodes to collect data, that meant the network need to keep the energy among the mobile nodes in balance. We used the number of remaining alive nodes as the parameter of the energy efficiency.

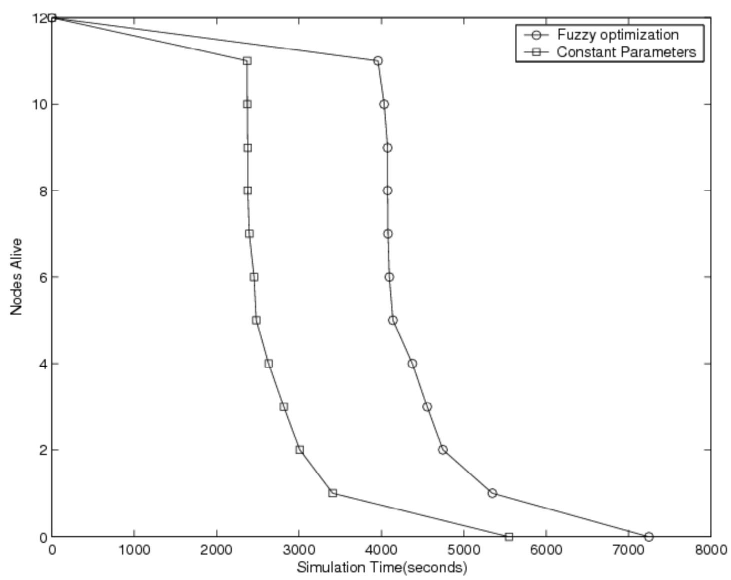


FIGURE 9: Energy Efficiency

We assumed P_{elec} was equal to 6.0×10^{-4} and ε_{fs} was equal to 6.0×10^{-4}. We assumed that the energy of each mobile node was 0.07 J.

When the remaining energy of a mobile node was lower than a certain threshold, the node was considered as ``dead''. In this simulation, we chose $1.2\times10^{-3}$ as the threshold. A sensor was ``dead'' meant it could not transmit/receive packets any longer, so it would be ignored by network. The number of nodes of mobile ad hoc networks which was below a certain threshold meant this network does not work.

As Fig.9 showed, after fuzzy optimization, the duration of the first node ``dead'' is 1.67 times longer than that of the constant parameters, which is 1589 seconds.

3. Networks Efficiency

The mobile ad hoc networks were used to collect data and transfer packets. The throughput of packets transmitted was one of the parameters to evaluate the networks efficiency. In our simulation, we assumed the collecting data distribution of the mobile node was Poisson distribution and the arriving interval was 0.2 second. Observing from Fig.10, the cross-layer optimization made a tradeoff between the real time traffic and the best effort traffic. For the real time traffic, after the cross-layer optimization, the throughput of the network was about 0.02% smaller than that of the constant parameters. However, for the best effort traffic, the throughput of the network was up to 71.99% larger. For the all the traffic case, after the cross-layer optimization, the throughput of the network was up to 32.52% larger, which meant the cross-layer optimization could improve the throughput performance for the whole system. As the performance of the average delay, the cross-layer optimization could achieve a "stable" throughput performance.

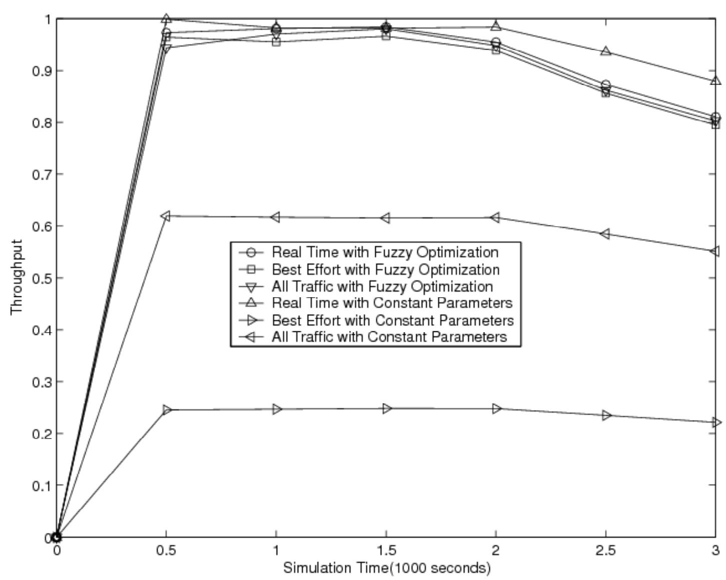


FIGURE 10: Network Efficiency

We introduced the fuzzy logic system in the cross-layer design. Comparing with other algorithms for cross-layer design, the fuzzy method could be flexible and simpler to implement and the performance outputs were also impressive.

6. CONCLUSION

Cross-layer design is an effective method to improve the performance of the mobile ad hoc network. We apply the fuzzy logic system to combine physical layer, data-link layer and application layer together. We selected ground speed, average delay and packets transmission successful ratio as antecedents. The output of FLS provides adjusting factors for the AMC, transmission power, retransmission times and rate control decision. Simulation shows the FLS application in cross-lay design could reduce the average delay, increase the throughput and extend the network lifetime. After the cross-layer optimization, the network performance parameters could also keep stable. In the future, we can consider other layers, such as network layer for the cross-layer design.

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