

An analytical model of MANET single-path and multi-path load balancing routing protocol based on Markov model

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Abstract— As the research of load balancing method in wireless self-organizing networks progresses, it was found that multi-path algorithms show superiority in terms of their abilities to improve packet delivery rate, increase transmission reliability, and handle network congestion and heavy traffic in a timely manner. In this paper, a new analytical model is presented to analyze and compare the superiority of multi-path algorithm over single-path algorithm in self-organizing networks based on four aspects: energy consumption, stability, throughput, and delay. The analysis is further confirmed from the simulation results, which show that the multi-path algorithm is 37% more stable than the single-path algorithm. Under the condition of the same number of packets sent, multi-path will be more energy efficient and time saving than single-path. In addition, multi-path nodes have higher throughput than single-path nodes with the same energy value.

Keywords— Analytical model, Energy consumption, Stability, Throughput, Delay.

I. INTRODUCTION

Mobile Ad Hoc Networks (MANETs) are collection of wireless mobile nodes. It is dynamically constructed without using any existing network infrastructure or centralized management[1-4]. MANET has the characteristics of no center, self-organization, dynamic topology, multi-hop routing, and easy deploying[5-7]. Ad hoc networks are used in a variety of scenarios. For example, emergency mobile communications, smart home connectivity, warrior-only combat systems, field work, and medical monitoring systems[7-9].

The capacity of wireless links is much lower than that of wired links, thus making it easier to cause network congestion and reduce network performance[10-13], which is the biggest challenge in mobile self-organizing networks. To cope with these problems, a series of routing algorithm have been developed for network communication to improve the performance, but different routing protocols have different advantages and disadvantages. Compared with the single-path algorithm, the multi-path algorithm has many advantages in fault tolerance, route reliability, QoS routing, etc. In this paper, we review the related routing protocols. And a new resolution model based on

finite Markov model is proposed for existing multi-path and single-path algorithms based on energy and hop selection factors, and the advantages and disadvantages of single-path and multi-path algorithms in wireless communication are analyzed in four aspects: energy consumption, stability probability, throughput and delay. The results show that the single-path algorithm is more energy-efficient when the amount of data is small. As the number of data increases, the multi-path algorithm can send more data faster and with better stability than the single-path algorithm.

The rest of this article is organized as follows: the second part summarizes the routing protocol; the third part introduces the related work in this field; the fourth part presents the analytical model and analyzes the performance of routing protocol; the fifth section introduces the simulation results and the last part summarizes the paper.

II. RELATED WORK

A. Multi-path Routing Protocol

This paper[14] proposes a new protocol called congestion-aware Fibonacci queue-based multipath routing protocol. Multiple paths are sorted at the route discovery node according to the round-trip time of packet requests and replies, and packets are distributed according to the Fibonacci sequence number by assigning different Fibonacci numbers from smallest to largest in order of round-trip time size.

Pathak and Kumar et al.[15] proposed a TALB-AOMDV protocol (Traffic Aware Load Balancing AOMDV), this method uses queue length and hop count as metrics for path selection. The Queue Length field is added to the RREQ packet that carries the total queue length that the path passes through. After performing path selection by comparing the buffer sizes on the path, data is distributed equally along the path to distribute the load among the paths.

A. Single-path Routing Protocol

In this paper[16], a new routing metric is introduced into the protocol which selects the path with maximum residual energy

and lightest load for data routing. The protocol uses the same mechanism as the AODV protocol for both route discovery and maintenance nodes. The new metric is used to select paths that have the smallest average size of the routing tables of all nodes (away from the traffic center) and the largest average residual power of all nodes. The metric is expressed as

$$\text{Minimize} \left(\frac{1}{N} \sum_{i=1}^N \frac{\text{sizeof}(rtb(i))}{Er(i)} \right) \quad (1)$$

Where $\text{sizeof}(rtb(i))$ is the size of the routing table of the node that participates in the route. $Er(i)$ is the residual energy of node i .

In this paper [17], a CBMLB protocol is proposed that uses a new parameter to measure network centrality based on channel busyness. As in equation (2), the channel busyness is defined as the ratio of channel-aware busy time plus transmission time to upper-layer channel-aware busy time plus transmission time plus idle time. Two fields are added to RREQ and RREP. Each node writes down its channel busy ratio in the packet up to the destination and source nodes and chooses the smallest sum of busy for transmission as shown in equation (3).

$$C(m) = \frac{\sum \text{Transmission} + \sum \text{busyness}}{\sum \text{idle} + \sum \text{Transmission} + \sum \text{busyness}} \quad (2)$$

$$C(p) = \frac{n}{n+1} c(n) + \frac{1}{n+1} c(n+1) \quad (3)$$

We think this paper can pick a few less busy lines for traffic allocation and change the single-path to multi-path, which can effectively improve the packet delivery rate and lower latency.

III. ANALYSIS MODEL

MANET is a wireless network that uses radio connections to broadcast packets over a transmission range, thereby facilitating communication in complex environments with limited access points. Figure 2 shows a stochastic network topology model where node S and node D want to communicate and there are n paths from source node S to destination node D . These paths are considered to be disjoint paths.

Assuming that each path has n_i nodes between S, D . ($i=1,2,3,\dots,n$ and $n_1 < n_2 < \dots < n_n$).

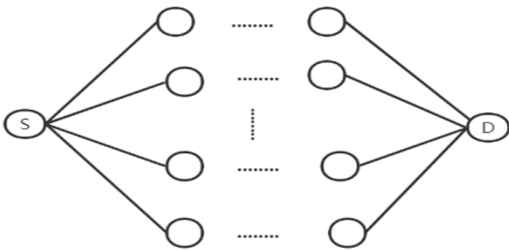


Figure 1. Random network topology model

Most of the previous routing models only consider a part of the factors that affect the delivery of data packets, for example, only a single factor such as the number of hops is considered, and the energy consumption and routing selection during the data transmission process are not considered. In this paper, we

propose a new analytical model that takes into account the residual energy and hop count to set up the path selection factor, and the packet sending path is selected by the established Markov model to compare the performance of Single-path and multi-path algorithm in terms of four aspects: energy consumption, stability probability, throughput and delay. The summary of the parameters used in this chapter is given in the following table 1.

TABLE 1. SUMMARY OF PARAMETER

Parameter	Meaning
n	Number of paths from S to D
n_i	Number of nodes of the i-th path
H_i	Energy consumed of the i-th path
E_{li}	Energy loss of the i-th path
λ	Probability of energy loss
f_l	Loss of potential energy to send a packet
f_c	Energy consumption for sending a packet
H_i	Number of hops in the i-th path
E_i	Residual energy of the i-th path
F_i	Selection factor
M	Smoothness parameters
d_i	Number of packets sent on the i-th path
d	Total number of packets in the transmission
E_l	the lost energy to send a packet
P_{ij}	Probability of path transfer
π_j	Steady-state probability of choosing path j
E_{sc}	Total energy consumed of a single-path
E_{mci}	The consumes energy of i-th path
p	Node damage probability
M_s	Single-path stability probability
M_m	Multi-path stability probability
TH_s	Single-path Throughput
TH_m	Multi-path Throughput
a	Number of packets in a set
T_s	Single-path transmission delay
T_m	Multi-path transmission delay
E_0	Initial energy of the node

We define the energy consumed by sending a data packet as f_c . The potential energy lost by sending a data packet is expressed as f_l , the lost energy fits a Bernoulli distribution with probability λ and the lost energy is E_l .

Using formula (4) to calculate the number of hops of path i .

$$H_i = n_i + 1 \quad (4)$$

Assuming that there are d packets waiting to be sent during a transmission from S to D . The packets sent each path are d_i .

$$d = \sum_{i=1}^n d_i \quad (5)$$

Energy consumed to send data on path i is defined as

$$E_{ci} = d_i f_c \quad (6)$$

The residual energy of the i -th path is defined as follows

$$E_i = \min(E_i - E_{ci} - E_l) \quad (7)$$

The path selection factor is defined as

$$F_i = \alpha E_i + (1 - \alpha) \frac{1}{H_i} \quad (8)$$

We define a path selection factor and a path selection model that conforms to a finite Markov chain to represent the path selection probability. As shown in Equation (9), (10)

$$P_{ij} = P(X_{n+1} = j | X_n = i) \quad (9)$$

$$P_{ij} = \begin{cases} \frac{F_i}{\sum_{i=1}^n F_i - F_i} & i \neq j \\ 0 & i = j \end{cases} \quad (10)$$

The transfer probability matrix of the path selection model can be derived as Equation (11)

$$\begin{bmatrix} P_{11} & P_{12} & \cdots & P_{1n} \\ P_{21} & P_{22} & \cdots & P_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ P_{n1} & P_{n2} & \cdots & P_{nn} \end{bmatrix} \quad (11)$$

The steady state convergence theorem is represented as follows

$$\lim_{n \rightarrow \infty} r_{ij}(n) = \pi_j \quad (12)$$

$$\pi_j = \sum_{k=1}^m \pi_k P_{kj} \quad (13)$$

$$\sum_{k=1}^m \pi_k = 1 \quad (14)$$

The steady-state probability equation can be obtained from Equation (12) (13)

$$\begin{cases} \pi_1 = \pi_2 P_{21} + \pi_3 P_{31} + \cdots + \pi_n P_{n1} \\ \pi_2 = \pi_1 P_{12} + \pi_3 P_{32} + \cdots + \pi_n P_{n2} \\ \vdots \\ \pi_n = \pi_1 P_{1n} + \pi_2 P_{2n} + \cdots + \pi_{n-1} P_{n-1n} \end{cases} \quad (15)$$

Solving the system of equations obtains the coefficient matrix as

$$\begin{bmatrix} P_{11} & P_{12} & \cdots & P_{1n} \\ P_{21} & P_{22} & \cdots & P_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ P_{n1} & P_{n2} & \cdots & P_{nn} \end{bmatrix} \quad (16)$$

$$\begin{bmatrix} -\left(\sum_{i=1}^n F_i - F_1\right) & F_1 & \cdots & F_1 \\ F_2 & -\left(\sum_{i=1}^n F_i - F_2\right) & \cdots & F_2 \\ \vdots & \vdots & \ddots & \vdots \\ F_n & F_n & \cdots & -\left(\sum_{i=1}^n F_i - F_n\right) \end{bmatrix} \quad (17)$$

Solving the system of equations yields the probability of choosing the j -th path as

$$\pi_j = \frac{F_j}{\sum_{i=1}^n F_i} \quad (18)$$

According to the above definition, we compare performance in four aspects: energy consumption, stability probability, throughput and delay, and give the corresponding proof as follows:

A. Energy Consumption

The single-path selects the t -th of path for transmission and the energy consumption is calculated as

$$E_{sc} = df_c + E_{lt} \quad (19)$$

The i -th path on the multi-path consumes energy as

$$E_{mci} = \frac{F_i}{\sum_{i=1}^n F_i} df_c + E_{li} \quad (20)$$

In the case of equal packet transmission

$$E_{mci} \leq E_{sc} \quad (21)$$

From equations (20) and (21), without considering the occurrence of congestion, it can be concluded that each path in the multi-path algorithm consumes less energy for transmission than the single-path algorithm.

B. Stable Probability

Stable probability is defined as the probability of successfully completing a data transfer process without interruption. Assuming that the probability of damage for each node is p ($0 < p < 1$).

The single-path algorithm selects the t -th path for data transmission, and the probability of stability of the single-path algorithm is

$$M_s = (1 - p)^{n_t} \quad (22)$$

Using multi-path algorithm for data transmission, the stable probability is:

$$M_m = 1 - \prod_{i=1}^n (1 - (1 - p)^{n_i}) \quad (23)$$

Using mathematical induction for proof :

When $n=1$

$$M_m = 1 - \prod_{i=1}^n (1 - (1 - p)^{n_i}) = (1 - p)^{n_1} \quad (24)$$

$$M_m = (1-p)^{n_1} \geq (1-p)^{n_i} = M_s \quad (25)$$

Assuming that for $n = m$

$$M_m = 1 - \prod_{i=1}^m (1 - (1-p)^{n_i}) \geq (1-p)^{n_i} = M_s \quad (26)$$

When $n = m + 1$

$$\begin{aligned} M_m &= 1 - \prod_{i=1}^{m+1} (1 - (1-p)^{n_i}) \\ &= 1 - \left\{ \prod_{i=1}^m (1 - (1-p)^{n_i}) \right\} (1 - (1-p)^{n_{m+1}}) \\ &= 1 - \prod_{i=1}^m (1 - (1-p)^{n_i}) + \left\{ \prod_{i=1}^m (1 - (1-p)^{n_i}) \right\} (1-p)^{n_{m+1}} \\ &\geq 1 - (1-p)^{n_i} + \left\{ \prod_{i=1}^m (1 - (1-p)^{n_i}) \right\} (1-p)^{n_{m+1}} \\ &\geq (1-p)^{n_i} = M_s \end{aligned} \quad (27)$$

This is proved by equations (25), (26) and (27)

$$M_m = 1 - \prod_{i=1}^n (1 - (1-p)^{n_i}) \geq (1-p)^{n_i} \quad (28)$$

So multi-path are more stable than single-paths and it is difficult to interrupt data transmission.

C. Throughput

Assuming that during the transmission process, as long as the path does not break down, it will continue to send data packets until the path energy is exhausted. We assume that each packet has the same size, then the throughput can be expressed as the number of packets sent

Single-path:

$$TH_s = \frac{E_0 - E_{lt}}{f_c} \quad (29)$$

Multi-path:

$$TH_m = \sum_{i=1}^n \frac{E_0 - E_{li}}{f_c} \quad (30)$$

From equation (29) and (30)

$$TH_m \square TH_s \quad (31)$$

It can be shown multi-path algorithm have better throughput than single-path algorithm. In the same situation, the multi-path algorithm can send more data than the single-path algorithm.

D. Delay

The data transmission delay is related to the processing power of the node and the number of node hops. There are d data packets waiting to be transmitted during one transmission. Defines the time to transmit a packet on path i as $1/F_i$. A set of data is composed of a packets, and each packet has the same size.

The single-path routing algorithm selects the t -th path for transmission and the delay is calculated as

$$T_s = \frac{d \times \frac{1}{F_t}}{d} \times a = \frac{a}{F_t} \quad (32)$$

The multi-path transmission delay is calculated as

$$\begin{aligned} T_m &= \frac{\sum_{i=1}^n d_i \times \frac{1}{F_i}}{d} \times a \\ &= \frac{\sum_{i=1}^n \frac{F_i}{\sum_{i=1}^n F_i} \times d \times \frac{1}{F_i}}{d} \times a \\ &= \frac{a}{\sum_{i=1}^n F_i} \end{aligned} \quad (33)$$

From equations (32) and (33), we can get

$$T_m < T_s \quad (34)$$

If the same packets are sent without regard to blocking, the multi-path algorithm transmission delay is less than the single-path algorithm transmission delay.

Combining these four aspects, the performance of multi-path algorithm is better than single-path algorithm during a single transmission in the same environment.

IV. SIMULATION RESULTS

The above model is simulated using Matlab and the four metrics for comparing performance were defined as follows.

Energy consumption: the amount of energy consumed to execute a complete transmission process.

Stable probability: the probability of successfully completing a data transfer process without interruption.

Throughput: the number of packets that can be sent if energy is depleted.

Delay: the time required to send a set of data packets.

Since in multi-path transmission, the more paths, the more energy will be consumed in the route discovery process, so we use 5 paths for simulation. The values of the simulation parameters are defined in Table 2.

TABLE 2. THE VALUES OF THE SIMULATION PARAMETERS

Parameter	Value
n	5
n_1	5
n_2	6
n_3	7
n_4	8
n_5	9
p	0.2
f_c	5
f_i	2
λ	0.2
α	0.75
d	500
E_0	3000

A. Energy Consumption

In order to compare the energy consumption of the two different algorithms during data transmission, We Suppose that during a transmission from the source node S to the destination node D, the number of data packets waiting to be transmitted is gradually increased from 0 to 500. Figure 2 shows the different energy consumption of the two algorithms.

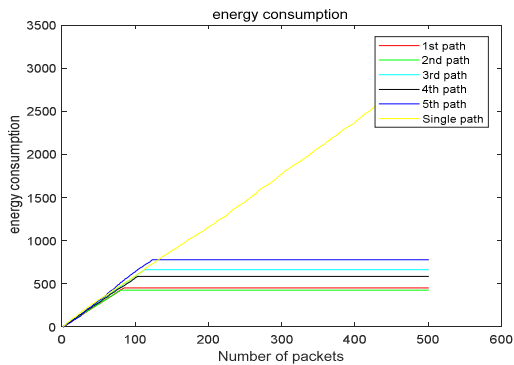


Figure 2. Energy Consumption Simulation Result

The experimental simulation results are shown in Figure 2, which uses single-path algorithm and multi-path algorithm for data transmission respectively. It can be seen that when the number of data packets is small, the required energy gradually increases, and the difference is not very obvious from the simulation results. When the number of packets increases, it is obvious that the energy required for a single path rises rapidly, while the multi-path has finished sending the data and the energy required on each path will be much less than the energy required on a single path. It avoids the situation that the transmission cannot be completed due to insufficient energy.

B. Stable Probability

During the transmission of data, as soon as one node on a path is damaged, the entire link is broken and when all available paths are damaged. In order to compare the stability of the single-path algorithm and the multi-path algorithm, we assume a damage probability of 0.2 for a single node for simulation experiments, and the stability probabilities of the single-path algorithm and the multi-path algorithm are shown in Figure 3.

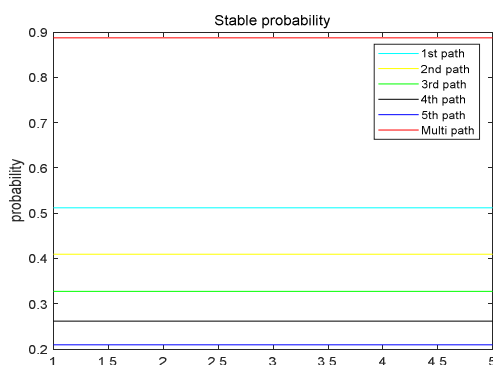


Figure 3. Stable Probability Simulation Result

From the figure, it can be seen that using single path for data transmission, the node has the highest stability probability of 51.2%, followed by 40.96%, 32.77%, 26.21% and 20.97%, while the multipath stability probability is 88.70%. It shows that multipath routing protocols are more stable than single path routing protocols, it can complete a data transmission more smoothly without being interrupted.

C. Throughput

The actual throughput of a computer network refers to the maximum rate that a device can receive without frame loss. In this model we set a certain size of each packet and the throughput can be expressed as the number of packets sent in a certain time. We assume that the amount of data is large enough. Data transmission is performed until the energy is exhausted without considering node damage interruptions. The initial energy value of 200 is set for each node and is gradually incremented by 10. The throughput of the single-path algorithm and the multi-path algorithm are shown in Figure 4.

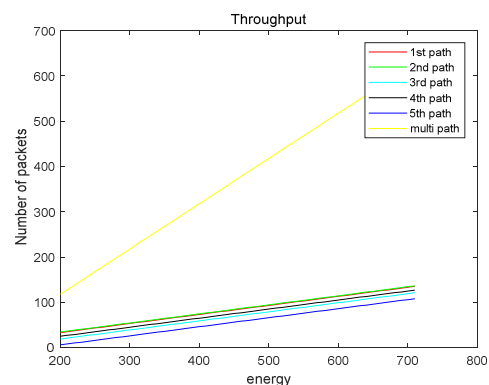


Figure 4. Throughput Simulation Result

The graph shows that as the node energy value grows from 200 to 700, the throughput of both the single-path algorithm and the multi-path algorithm grow gradually, but the throughput of the multi-path algorithm grows faster than the single-path algorithm. As the energy value gets larger, the difference between the throughput of the multi-path algorithm and the single-path gets larger.

D. Delay

In this paper our delay is considered as propagation delay only, the time required for data propagation from the source node S of this link to the destination node D is the propagation delay. In order to compare the effect of the number of packets on the delay, we gradually increase the number of packets and use a single-path algorithm and a multi-path algorithm for packet transmission respectively. In our experiments, we gradually increased the packets from 0 to 500, and then came to test the propagation delay, and the delay results are shown in Figure 5.

The figure shows that for the same amount of data sent, the multipath routing protocol has a smaller delay than the single

path routing protocol. This delay is more obvious when more and more packets are sent, because the more packets are sent, the less energy the node has, resulting in less processing power and a correspondingly higher delay.

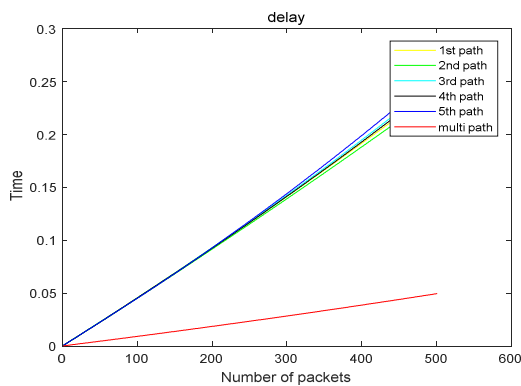


Figure 5. Delay Simulation Result

V. CONCLUSION

This paper addresses the performance of multipath routing protocols and single path routing protocols. The randomness and the possible energy loss during transmission are considered, and the path selection is established in the form of a finite Markov model with the residual energy and the number of path hops as the selection conditions. The four metrics of energy consumption, stability probability, throughput, and delay in single-path and multi-path data transmission are analyzed theoretically and simulated experimentally, and the experimental results prove that the multi-path routing protocol performance is better than the single-path routing protocol performance. Further research in the future will focus on the path congestion and the impact of link coupling on performance.

REFERENCES

- [1] Sivakumar, B., N. Bhalaji and D. Sivakumar, A Survey on Investigating the Need for Intelligent Power-Aware Load Balanced Routing Protocols for Handling Critical Links in MANETs. *Scientific World Journal*, 2014. 2014: p. 138972.
- [2] Patel, R.S. and P. Kamboj, An Efficient Delay-Based Load Balancing using AOMDV in MANET. 2020: Proceedings of First International Conference on Computing, Communications, and Cyber-Security (IC4S 2019).
- [3] Irudayarajan, S., et al. A Review on Load Balancing for Reducing Congestion in Mobile Ad-Hoc Networks. in *International Conference on Soft-computing and Network Security*.
- [4] Bennis, I., et al. A Realistic Multi-path Routing for Ad Hoc Networks. in *GLOBECOM 2015 - 2015 IEEE Global Communications Conference*. 2014.
- [5] Roth, U., Highly Dynamic Destination-Sequenced Distance-Vector Routing. *Proc Acm Sigcomm94* Aug, 1994: p. 234-244.
- [6] Ogier, R., Topology dissemination based on reverse forwarding (TBRPF). *Ietf Rfc*, 2004.
- [7] Perkins, C., Ad hoc on-demand distance vector (AODV) routing. *Rfc*, 2003.
- [8] Johnson, D., The Dynamic Source Routing Protocol (DSR) for Mobile Ad Hoc Networks for IPv4. Request for Comments : 4728, 2007.
- [9] Billington, J. and Y. Cong, On Modelling and Analysing the Dynamic MANET On-Demand (DYMO) Routing Protocol. Springer-Verlag, 2009.
- [10] Yu-Qi, H.U. and N.X. Zhang, Zone routing protocol based on hierarchical structure. *Journal of Yanshan University*, 2014.

- [11] Radhakrishnan, S., et al. DST-A routing protocol for ad hoc networks using distributed spanning trees. in *Wireless Communications & Networking Conference*. 1999.
- [12] Malviya, L., A.A. Wao and S. Sharma, New Load Balanced Multi-path Dynamic Source Routing Protocol for Mobile Ad-HOC Network. *International Journal of Computer Applications*, 2013. 61(19): p. 25-27.
- [13] Herberg, U., et al., The Optimized Link State Routing Protocol Version 2. 2014.
- [14] Naseem, et al., Congestion-Aware Fibonacci Sequence Based Multi-path Load Balancing Routing Protocol for MANETs. *Wireless personal communications: An International Journal*, 2015. 84(4): p. 2955-2974.
- [15] Pathak, G. and K. Kumar, Traffic aware load balancing in AOMDV for mobile Ad-hoc networks. *Journal of Communications & Information Networks*, 2017.
- [16] Hao, J., et al. An Adaptive Load Balanced on Demand Routing Protocol. in *International Conference on Networks Security*. 2009.
- [17] A. A. Aouiz, S. B. Hacene and P. Lorenz, "Channel Busyness Based Multi-path Load Balancing Routing Protocol for Ad hoc Networks," in *IEEE Network*, vol. 33, no. 5, pp. 118-125, Sept.-Oct. 2019, doi: 10.1109/MNET.2019.1900036.



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