A QoS-supported Multi-constrained Routing Strategy Based on Ant-Colony Optimization for Named Data Networking

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***Abstract*—Named data networking (NDN) is a typical representation and implementation of content-centric networking (CCN) and serves as a basis for the next-generation Internet. To the best of our knowledge, very few studies have considered multi-metric constraints on routing strategies. Therefore, This paper proposes a multi-constrained routing strategy based on ant-colony optimization (ACO) to satisfy the multi-metric requirements for supporting the QoS of NDN. In the proposed routing strategy, namely ACO-McQoS, bandwidth, delay, and cost are defined as metrics. An optimal combination of these metrics is chosen to accommodate different QoS requests. An extensive simulation is conducted among the shortest path routing, maximum bandwidth path routing, random path routing, and ACO-McQoS. The simulation results show that the proposed routing strategy outperforms other.**

Keywords—Named data networking, content-centric networks, quality of service, fault-tolerant routing, ant-colony optimization

I. INTRODUCTION

In the information era, many users only focus on the information itself instead of its location. However, the traditional location-aware, host-to-host, or machine-to-machine communication modes are unable to meet current needs. Therefore the information-centric networking (ICN) concept has been proposed and serves as a promising paradigm for future Internet architecture [1-2]. Among several ICN-based approaches and activities, CCN [3-4] has been considered as a typical resolution scheme of ICN, and it will be used to build communication systems on named data, instead of host-to-host or machine-to-machine connections, rendering a robust, simple, and scalable network architecture [5].

NDN [6] is a major implementation of CCN, which routes and forwards packets based on names. NDN contains two types of packets: interest packets, which contain the name of desired data for subscribers, and data packets, which contain data content for subscribers. To fetch an information object, a subscriber sends an interest packet with the name of the information object to the NDN transport network to explore potential target data. The publisher then sends back target data in the form of a data packet using the reversed routing of the interest packet. All packets are forwarded according to the hop-by-hop model by content routers (CRs). Each CR has three data structures: the content stores (CS), the pending interest table (PIT), and the forwarding information base (FIB). The CS caches data comes from publishers. The PIT includes a set of faces to handle interest packets that are waiting to receive data packets. If a data packet is received, the corresponding interest packet will be consumed. The FIB contains NDN route entries and maps incoming interest packets to a suitable face(s) for searching the target publisher. If the face is not matched, the interest packet will be discarded.

II. ROUTING IN NDN

Routing is critical for current NDN research [7-8], it directly affects the fault-tolerant performance of NDN in terms of packets' successful delivery probability. Three forwarding approaches are included in the original NDN proposal [6]. The simplest approach randomly selects a face in a FIB to forward an interest packet. However, this approach cannot guarantee that a subscriber obtains stable and optimal network performance. The second approach simultaneously sends an interest packet to all faces of a FIB. This approach potentially reduces time consumption but increases network load. The third is selecting a smart face searched by intelligent evolutionary algorithm such as ant-colony optimization in a FIB to forward interest packets. This approach not only achieves good network load balance, but also guarantees that a subscriber will obtain stable and optimal network performance. Li et al., [9-10] proposed a QoS-aware routing algorithm

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called the greedy ant colony forwarding algorithm (GACF); however, this method divides the network into multiple domains causing a loss in global significance. Y Zhang et al., proposed an ant colony based extensible forwarding (ACEF) strategy [11], which integrates ACO into a multi-attribute decision making (MADM) and applies a maximum deviation approach to forward interest packets with automatically assigned attribute weights. A Kerrouche et al. proposed a packets forwarding strategy [12] named ant colony based QoS-aware forwarding strategy (AC-QoS-FS), which can detect network parameters in real time to update the interface ranking, thus satisfy NDN network's QoS.

In this paper, a QoS-aware routing strategy based on ant-colony optimization for multi-constrained QoS traffic is proposed. This method, namely the ACO-McQoS routing strategy, identifies a minimal cost path for an interest packet that also satisfies the multi-constrained QoS requirement, i.e., bandwidth and delay constraints. This method also increases the reception ratio of data packets.

III. ACO-MCQOS ROUTING STRATEGY

A. NDN routing and forwarding mechanism

In this section, we detail the routing process and packet format of the proposed ACO-McQoS routing strategy. We improve upon the conventional NDN routing strategy [6] in two particular ways. First, based on the previous work [13], we extend a FIB by adding an additional item defined as pheromone, which apply the ant-colony based forwarding process. Here is the metric of faces in FIB, which is used to determine the next face selective probability in ant-colony based forwarding process, the larger of its value, the greater of the probability that the face be chosen, where s denotes the source name and j represents the associated faces in the FIB of node i. We probabilistically choose a face by calculating the pheromone values of the pheromone item. The extended FIB table is given in Fig. 1.

Content Name	faces	Pheromone
Google.com/voice/...	0	$\tau_{n0}^{G}(t)$
	1	$\tau_{n1}^{G}(t)$
	2	$\tau_{n2}^{G}(t)$
Youtube.com/videos/...	1	$\tau_{n1}^{Y}(t)$
	3	$\tau_{n3}^{Y}(t)$

Fig. 1 Example of an extended FIB

Second, we introduce the response packet in the NDN signaling system to: (1) release an invalid interest packet, for which there is no suitable data for mapping; (2) update the pheromone value in FIB. In the ACO-McQoS routing strategy, each packet is treated as an ant.

There are three types of ants in NDN extended by ACO-McQoS: interest ants, data ants and response ants, which denote interest packets, data packets and response packets, respectively. When an NDN subscriber requests a specific information object, an interest ant is issued and sent into the NDN transport networks to search for the desired information. The interest ant contains the constrained QoS of the expected data and forwarding information, i.e. minimal bandwidth and time stack. The minimal bandwidth denotes bandwidth bottleneck on the path the interest ant has traveled and the time stack is used to record the total forwarding time of the interest ant. Once an intermediate CR receives an interest ant, it checks its cache to find whether there is the data matches the requirement of the interest ant, if it has, the CR will sends the matching data to the subscriber, otherwise, it selects a suitable face depending on the corresponding pheromone value in the FIB to forward the packet. If the expected data is found, it is returned to the subscriber on the reverse path of the interest ant. Otherwise, the CR, which holds the failed searching interest ant, will generate a response ant, marked with the same name as the interest ant, to release the face(s) records that cannot be used to explore the data. Both the data ants and response ants copy the forwarding information to update the pheromone value in NDN CRs from the interest ant. Fig.2 shows the forwarding process of the three types of packets in an NDN CR.

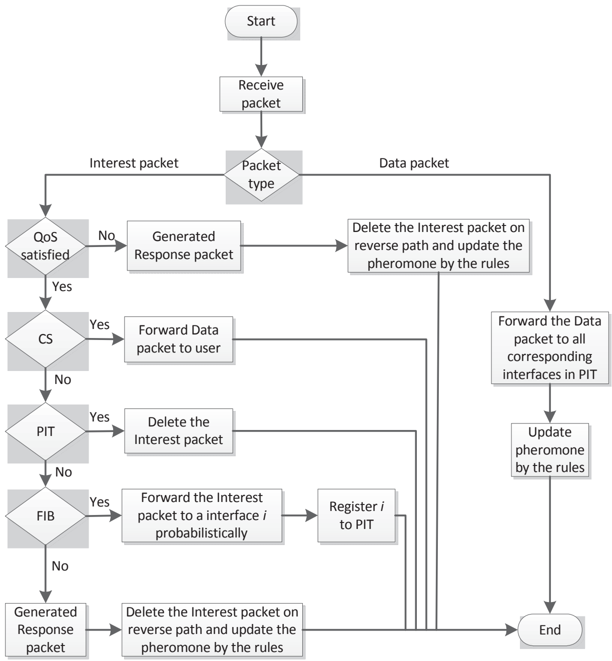

Fig. 2 The forwarding model in an NDN CR

B. Multi-constrained QoS and design of the ACO-McQoS algorithm

The multi-constrained QoS routing strategy attempts to find a minimal-cost route that can satisfy multiple constraints, such as bandwidth and delay. In general, multi-constrained path selection is an NP-complete problem that cannot be solved in polynomial time [14]. Heuristic algorithms, such as ant-colony optimization with polynomial time complexity, are often used to deal with this problem. Two examples of heuristic algorithms are the QoS routing algorithm based on the culture-ant colony algorithm in [15] and the improved ant colony algorithm with multi-strategies for the QoS routing problems in [16].

1) Multi-constrained QoS

We consider the network as a graph $G=(V,E)$, where

V is the set of CRs, and E is the set of links, which integrate the CR parameters. For a link $(i, j) \in E$, we define three parameters: $B(i, j)$, $D(i, j)$, and $C(i, j)$ which represent the bandwidth, delay, and cost of link (i, j), respectively. We also define $R(i^*)$ as a path, where i^* represents an interest ant in the NDN network, which intends to find the requested information object. Then we have

$$B(R(i^*)) = \min_{(i,j)\in R(i^*)} \{B(i, j)\} \tag{1}$$

$$D(R(i^*)) = \sum_{(i,j)\in R(i^*)} D(i, j) \tag{2}$$

We define $B_{\min}$ and $D_{\max}$ as the QoS constraints, which represent the minimum bandwidth requirement and the maximum delay permission, respectively. The QoS requirement $R(i^*)$ should satisfy

$$B_{\min} \le B(R(i^*)) \tag{3}$$

$$D_{\max} \ge D(R(i^*)) \tag{4}$$

2) ACO-McQoS algorithm design

a. The rules of state transition

The selection of faces in NDN CRs depends on the states transition rule. In this paper, we use the pseudo-random probabilistic selection rule for faces selection. The selection probability P_{ij}^s for the next face j in CR i of an interest ant exploring the data source s, is given by

$$j = \begin{cases} \arg \max_{f\in allowed_{FIB}} \left\{ \left(\tau_{if}^s(t)\right)^\alpha \cdot \left(\eta_{if}^s(t)\right)^\beta \right\}, & if\ r \le r_0 \\ J, & else \end{cases} \tag{5}$$

$$P_{ij}^s = \frac{\left(\tau_{if}^s(t)\right)^\alpha \cdot \left(\eta_{if}^s(t)\right)^\beta}{\sum_{f\in allowed_{FIB}} \left(\tau_{if}^s(t)\right)^\alpha \cdot \left(\eta_{if}^s(t)\right)^\beta} \tag{6}$$

where $\tau_{if}^s(t)$ denotes the pheromone concentration of face f for an interest ant arriving at i and destined for s, J is the interface calculated from the probability distribution in Eq.(6) in the FIB interface set, α reflects the importance of pheromone concentration on the movement of ants, β is the desirability value, which reflects the influence of heuristic value on the path selection of ants, $allowed_{FIB}$ in (5) and (6) is the set of next faces in the FIB corresponding to s, r is a random number ranging from 0 to 1, and r_0 is a constant for adjusting the ratio of random selection, and $\eta_{if}^s(t)$ denotes the desirable heuristic value with

$$\eta_{if}^s(t) = \left(D(i,f)\right)^{-1} \cdot B(i,f) \tag{7}$$

b. Pheromone update rules

Pheromone updating is completed by data and response ants. If CR i receives a data ant from a data source s on face j, the pheromone values for j will be updated by positive feedback; on the other hand, if a response ant is received, it will be updated by negative feedback. Pheromone values are updated according to

$$\tau_{ij}^s(t+1) = (1-\rho)\cdot \tau_{ij}^s(t) + \rho\cdot \gamma_{ij} \cdot \Delta\tau_{ij}^s(t) \tag{8}$$

where the value of ρ is the deterministic pheromone evaporation rate, γ_{ij} is defined as a feedback factor in this paper, which decides the update of pheromone is positive, negative or not updated, and $\Delta\tau_{ij}^s(t)$ denotes the increment of pheromone at time t. γ_{ij} is given by

$$\gamma_{ij} = \begin{cases} +1, & \text{updated by } \textit{data} \text{ ant} \\ -1, & \text{updated by } \textit{response} \text{ ant} \\ 0, & \text{else} \end{cases} \tag{9}$$

and $\Delta\tau_{ij}^s(t)$ is given by

$$\Delta\tau_{ij}^s(t) = e^{-Q\cdot\left(C_n^k - C_{\min}^k\right)} \tag{10}$$

Here, $C_{\min}^k$ denotes one of the minimum cost consumption of all interest ants, C_n^k denotes the cost consumption of any interest ant n during the iteration times k, and Q is the decay constant.

c. Packets forwarding strategies of ACO-McQoS

In NDN, interest packets and data packets obey different forwarding strategies. In ACO-McQoS applied NDN networks, interest ants is responsible for selection of faces that to be forwarded in FIBs and PITs, data ants and response ants are responsible for network state's calculation and update $\tau_i^s(t)$ values in PITs of CRs along the path that selected by interest ants. To adapt to different packets forwarding requirements, ACO-McQoS proposes two packets forwarding strategies that have been embodied as Algorithm 1 and Algorithm 2 for interest ants and data/response ants respectively.

Algorithm 1 interest ant strategy

```
ForwardingStrategy:: OnIntersetAnt()
{
  if CS contains data
    Create data ant;
    interest ant terminate;
  else if PIT contains interest ant entry
      Add the face to PIT entry;
      interest ant terminate;
  else
    if j ∈ allowed_FIB then
      r ← random();
  if r ≤ r0 then
```

for all j ∈ $allowed_{FIB}$ **do**
Choose face u (u ∈ $allowed_{FIB}$) referring to (5);
end for
else
for all j ∈ $allowed_{FIB}$ **do**
Calculate empirical probability distribution F referring to (6);
end for
Choose u ← F;
Create PIT entry;
end if
end if
}

Algorithm 2 data/response ant strategy

ForwardingStrategy:: OnDataAnt()/OnResponseAnt()
{
Find the corresponding faces J of PIT entry;
for j ∈ J
Forwarding data/response ant to j;
Release the corresponding entry of PIT;
Running updating rules referring to (8);
end for
}

IV. SIMULATIONS

To verify the efficiency and effectiveness of the ACO-McQoS routing strategy, we compare its performance with the three typical routing approaches used by current NDN projects [9]. Specifically, we compare it with shortest path routing (SR), maximum bandwidth path routing (MR), and random path routing (RR). We set $\alpha = 3$, $\beta = 1$, $\rho = 0.25$, and $Q = 5$. Furthermore, we define the failure rate $P_{failure}$ as

$$P_{failure} = \frac{Count_{Interest} - Count_{Data}}{Count_{Interest}} \quad (11)$$

where $Count_{Interest}$ and $Count_{Data}$ are the number of interest ants sent and data ants received, respectively.

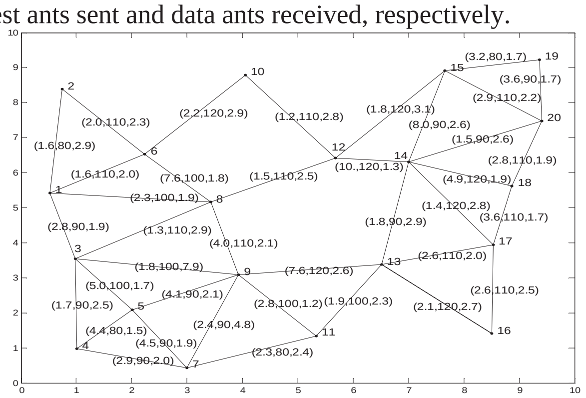

Fig. 3 The network topology

We use the improved Salama algorithm [17] to randomly generate a NDN topology that contains 20 CRs.

As shown in Fig.3, each edge is represented by (c, b, d), where c, b and d denote the cost, bandwidth, and delay, respectively. We used NS-2 simulator combined with Matlab.

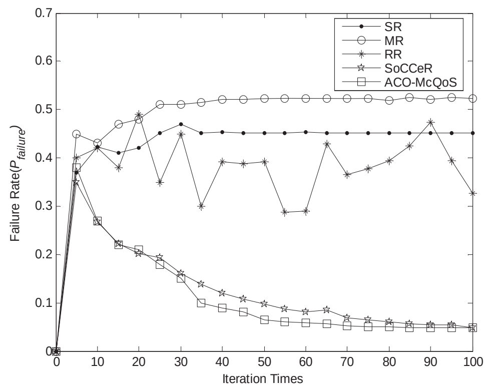

Fig. 4 Failure rate comparison of different routing protocols with $B_{\min} = 80$ and $D_{\max} = 18$

Figure 4 shows the performance comparison between the SR，MR, RR, SoCCeR and ACO-McQoS strategies for interest ant failure rates when QoS requirements are $B_{\min} = 80$, $D_{\max} = 18$. Fig. 4 shows that the interest ant failure rates of SR, MR, RR and SoCCeR are higher than that of ACO-McQoS at most iteration. This is a result of the fact that SR and MR only consider a single metric, which renders the other metric is unable to be satisfied. Moreover, RR's NDN CRs randomly select faces to forward interest ants, fail to satisfy the QoS requirement. On the contrary, in ACO-McQoS we consider that the combined constraint metrics of delay and bandwidth can satisfy a path. In addition, Fig. 4 also shows that the interest ant failure rates of SoCCeR is simlar to our ACO-McQoS. This is because that the SoCCeR use service load and path delay between a node and service as the metrics for service selection, SoCCeR routes service requests selectively to service instances with lighter loads and lower delay. However, ACO-McQoS has a higher failure rate at the first few iteration times of simulation. The study process also limits the efficiency of ACO-McQoS at the first few iterations as well. This is a result of ACO-McQoS's lack of exploring experience; this situation is resolved as prior exploring experience is studied.

Figure 5 shows the performance comparison between the SR，MR, RR, SoCCeR and ACO-McQoS strategies of interest ant average cost and failure rates when the QoS requirements are $B_{\min} = 100$, $D_{\max} = 15$. As illustrated in this figure, ACO-McQoS outperforms over other strategies on the two performance comparisons. Fig.5 illustrates that, under higher QoS requirements condition, though all the strategies have higher failure rates, ACO-McQoS still maintains in low level. ACO-McQoS has lower failure rate increment than that of other strategies under higher QoS requirements condition.

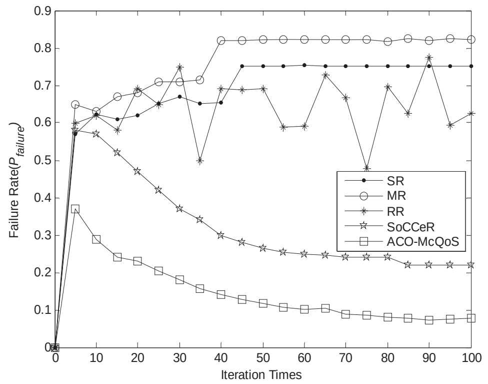

Fig. 5 Failure rate comparison of different routing protocols with $B_{\min} = 100$ and $D_{\max} = 15$

Without loss of the generality, we randomly set the QoS constraint values $B_{\min} = 80$ and $D_{\max} = 18$ under user node which is connected to CR2 and data source node which is connected to CR16 network scenario. Then we change the constraint values $B_{\min} = 80$ and $D_{\max} = 18$ to $B_{\min} = 100$, $D_{\max} = 15$. Tab.1 shows the optimal route searched by ACO-McQoS. We observe that because of the change of the constraint values, the cost and delay of route change, the optimal path also changes. The ACO-McQoS strategies can intelligently generate different optimal paths based on different constraint values.

Table.1 Optimal routing by ACO-McQoS

Constraint	Best Route	Cost	Delay
$B_{\min} = 80$ $D_{\max} = 18$	2→1→3→4→7→ 11→13→16	15.3	16.7
$B_{\min} = 100$ $D_{\max} = 15$	2→6→1→8→9→ 11→13→16	16.7	14.5

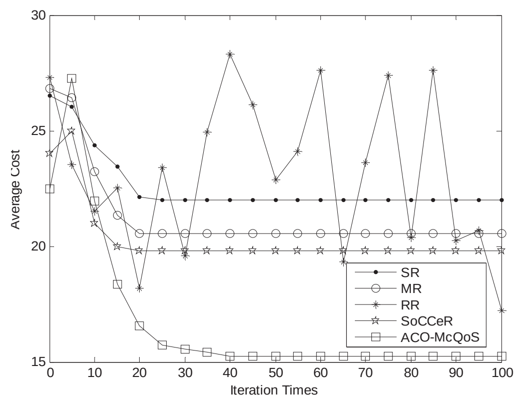

Fig. 6 Average cost comparison of different routing protocols with $B_{\min} = 80$ and $D_{\max} = 18$

Fig.6 shows the performance comparison between the SR, MR, RR, SoCCeR and ACO-McQoS strategies for interest ant average cost when QoS requirements are $B_{\min} = 80$, $D_{\max} = 18$. From Fig.6, we observe that ACO-McQoS has a lower cost than SR, MR, RR and SoCCeR on most simulation iteration times. In contrast to SR, MR, RR and SoCCeR, ACO-McQoS considers the impact of cost on NDN network performance.

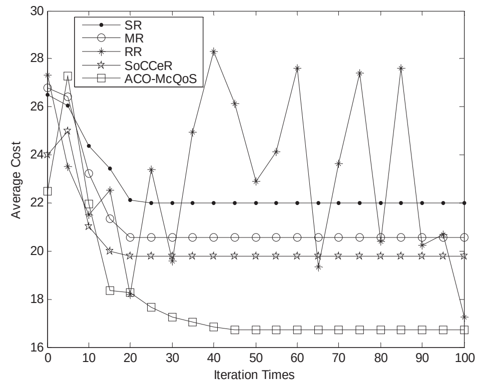

Fig.7 Average cost comparison of different routing protocols with $B_{\min} = 100$ and $D_{\max} = 15$

Fig.7 shows the performance comparison between the SR， MR, RR, SoCCeR and ACO-McQoS strategies of interest ant average cost when the QoS requirements are $B_{\min} = 100$, $D_{\max} = 15$. As illustrated in this figure, ACO-McQoS outperforms over other strategies on average cost. The average cost of ACO-McQoS in Fig.7 becomes larger than that of in Fig.6. It is due to ACO-McQoS selects a path with higher cost to satisfy higher QoS requirements.

Figures 8 and 9 show the performance of ACO-McQoS under parameter values ρ =0.01, 0.1, 0.25, 0.5, and 0.75. Fig. 8 shows that a larger value of ρ tends to reduce failure rate. When ρ is large, the pheromone trail is updated in large steps. Hence, prior information is more strongly studied.

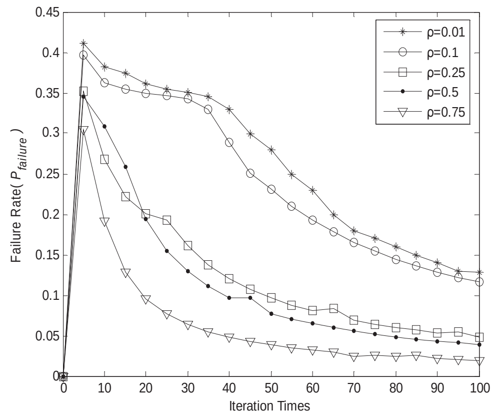

Fig. 8 Failure rate of ACO-McQoS with $\alpha = 3$, $\beta = 1$

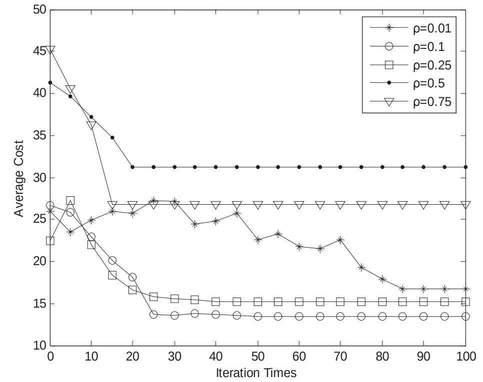

Fig. 9 Average cost of ACO-McQoS with $\alpha = 3, \beta = 1$

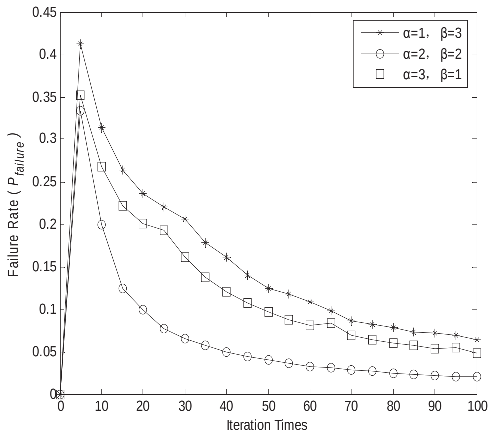

Fig.10 Failure rate of ACO-McQoS with $\rho = 0.25$

Fig.10 shows the convergence values of the failure rate for ACO-McQoS. From this graph, we see that, under the same iteration time conditions, the failure rate is smallest when $\alpha = 2, \beta = 2$.

V. CONCLUSION

NDN has been regarded as an ideal candidate architecture for future networks. In this paper, we proposed a multi-constraint, QoS-supported routing strategy based on ant-colony optimization (ACO-McQoS) for NDN networks. Compared with other routing strategies, i.e. SR, MR, RR and SoCCeR, our approach yields better performance in terms of failure rate and cost, enhances the routing robustness. We compared the performance of our proposed strategy to SR, MR, RR and SoCCeR, and provided a detailed analysis for selecting the important parameters for the ACO-McQoS strategy. Two issues require further study. Firstly, we plan to consider other intelligent optimization algorithms, such as particle swarm optimization (PSO), and secondly, packets congestion should be considered to gain more generality in our proposed routing strategy.

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