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Reliability-guaranteed multipath allocation algorithm in mobile network

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Abstract

The mobile network allows redundant transmission via disjoint paths to support high-reliability communication (e.g., ultrareliable and low-latency communications [URLLC]). Although redundant transmission can improve communication reliability, it also increases network costs (e.g., traffic and control overhead). In this study, we propose a reliability-guaranteed multipath allocation algorithm (RG-MAA) that allocates appropriate paths by considering the path setup time and dynamicity of the reliability paths. We develop an optimization problem using a constrained Markov decision process (CMDP) to minimize network costs while ensuring the required communication reliability. The evaluation results show that RG-MAA can reduce network costs by up to 30% compared with the scheme that uses all possible paths while ensuring the required communication reliability.

KEYWORDS

6G mobile network, communication reliability, constrained Markov decision process (CMDP), intelligent mobile core network

1 | INTRODUCTION

The International Telecommunication Union-Recommendations (ITU-R), recently, classifies mobile network service types as enhanced mobile broadband (eMBB), massive machine-type communications (mMTC), and ultrareliable and low-latency communications (URLLC) according to the characteristics of the services [1]. The 3rd Generation Partnership Project (3GPP) defines some standards to ensure that the quality of service is met efficiently for each service type since each service type has unique characteristics. Specifically, to support URLLC service, the 3GPP standard permits the mobile network to conduct the redundant transmission for a specific user [2–4]. That is, the mobile network can allocate several paths to the user and transmit the replicated packets to the user through those paths [5, 6].

Intuitively, we can achieve higher communication reliability by using more paths for redundant transmission. However, more paths indicate increased network costs (e.g., traffic and control overhead) [7]. To balance the trade-off, several works have been proposed, which can be divided into two categories based on the target networks: works for wireless network [7–11] and works for the wired network [12–14]. However, since these studies did not consider the unique characteristics of the mobile network (e.g., path setup time and the dynamicity of the mobile network's reliability), they cannot effectively achieve high communication reliability and/or reduce network costs in the mobile network.

The corresponding signaling procedure must allocate paths in the mobile network, [2, 5], which means a certain amount of path setup time is required. This implies that users cannot use new paths immediately to ensure communication reliability. Furthermore, the reliability of each path varies dynamically due to user mobility and network congestion. Thus, even if a path has high reliability at a specific time, it may no longer be reliable after the path setup time. In summary, to ensure the required communication reliability in the mobile network, appropriate paths should be allocated by considering the path setup time and the dynamicity of path reliability. Meanwhile, 3GPP has defined a new network function called the network data analytic function (NWDAF) that can derive various analytics using machine learning and artificial intelligence (AI) techniques [15, 16]. As an example of analytics, it is assumed that NWDAF can estimate the dynamicity of the reliability of paths.

In this study, we propose a reliability-guaranteed multipath allocation algorithm (RG-MAA). NWDAF estimates the path setup time and the dynamicity of path reliability in RG-MAA. Following that, it can allocate appropriate paths based on the estimated information. We develop an optimization problem using a constrained Markov decision process (CMDP) [17] to minimize network costs while ensuring communication reliability. The evaluation results show that RG-MAA can reduce the average network cost by up to 30% compared with the scheme allocating all possible paths while ensuring communication reliability. Furthermore, it has been discovered that RG-MAA adapts and determines the number of allocated gNBs and CN-paths based on the operating environment (e.g., required reliability).

The contributions of this paper are summarized as follows: (1) to the best of our knowledge, this is the first work to determine the paths over wireless and wired networks for redundant transmission by jointly considering path setup time and dynamicity of path reliability, and (2) extensive simulation results are presented and analyzed in various environments to provide valuable guidelines for designing a mobile network for the ultrareliable communication.

The remainder of this study is structured as follows. The related work is summarized in Section 2. The system model is described in Section 3, while the CMDP model is explained in Section 4. Evaluation results are given in Section 5 and followed by the concluding remarks in Section 6.

2 | RELATED WORKS

A lot of work has recently been done to achieve reliable communication [7–14]. These works can be divided into two categories based on the target environment: (1) works for the wireless network [7–11]; and (2) works for the wired network [12–14].

Mahmood and others [7] proposed an admission mechanism for controlling the number of users for multi-connectivity to improve reliability while preventing wireless resource abuse. Rao and others [8, 9] proposed a dynamic packet duplication control algorithm to improve radio resource usage while effectively satisfying the required reliability. Mahmood and others [10] conducted an analytical study on the outage probability for the multiconnectivity 5G access network environment. Guzman and others [11] introduced a centralized predictive flow controller that forecasts wireless channel quality at the access network to ensure reliable communication.

Tan and others [12] proposed a reliable intelligent routing mechanism for selecting the best traffic data routing path to support reliable connectivity. Barakabitze and others [13] proposed a software-defined network (SDN)-based multipath allocation approach to satisfy the required reliability. Qu and others [14] devised a mixed integer linear program to jointly determine the location of the network function and routing path.

However, these studies were limited to only access networks (i.e., wireless networks) or core networks (i.e., wired networks). Furthermore, they did not consider the path setup time for the corresponding singling procedures among network functions when allocating paths [2].

3 | SYSTEM MODEL

As shown in Figure 1, we consider a mobile network that consists of the access and core networks [5]. The packets

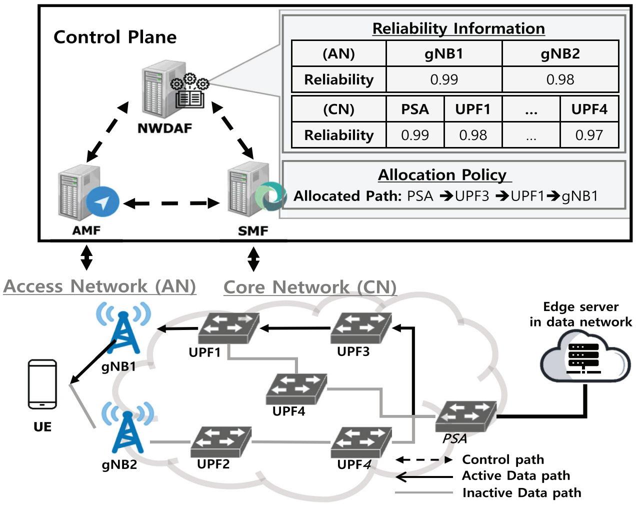

FIGURE 1 System model

traverse the core and access networks to provide the service from a server in the data network to a user on the mobile network. Specifically, several user plane functions (UPFs) in the core network sequentially forward packets to the access network. The packets are then forwarded to the user by the access network through specific gNBs.

There are C core network paths known as CN-paths, and each CN-path consists of several UPFs. Note that all CN-paths must include a PDU session anchor (PSA), which is a specific UPF that is directly connected to the data network. Meanwhile, G gNBs are deployed in the access network. The user can be assigned several gNBs and CN-paths simultaneously [5]. The maximum number of allocated CN-paths and gNBs is assumed to be m_{AN} and m_{CN}, respectively.[1] Each gNB and CN-path has a different packet error rate due to the dynamic network environment (e.g., user mobility, obstacles near the user, and network congestion). The packet error rates of gNB g and CN-path c are represented by $\varepsilon_{\text{AN},g}$ and $\varepsilon_{\text{CN},c}$, respectively. These rates can be maintained in NWDAF [5, 16]. NWDAF calculates the reliability of gNBs and CN-paths based on the maintained packet error rates. Specifically, the reliability of gNB g and CN-path c,$r_{\text{AN},g}$ and $r_{\text{CN},c}$, can be calculated as $1-\varepsilon_{\text{AN},g}$ and $1-\varepsilon_{\text{CN},c}$, respectively. Note that the reliability of gNB or CN-path is defined in this study as the probability that the packet is delivered without error through that gNB or CN-path.

NWDAF determines the optimal gNBs and CN-paths to be allocated to the user by considering the reliability of gNBs and CN-paths and triggers the path setup procedures with the network functions (e.g., AMF, SMF, gNBs, and UPFs) [2, 5]. After a certain amount of path setup time [18], the user is assigned new paths that consist of the determined gNBs and CN-paths. Following that, PSA replicates the packets as many as the number of allocated CN-paths and simultaneously transmits the replicated packets via those CN-paths [3, 5]. When gNBs receive the packets, they check to see if the received packet has already been sent or not. If the packet has not been sent previously, gNBs will forward it to the user. Otherwise, gNBs will discard the packet. Meanwhile, when the user receives the same packet from gNBs, the user discards the packet that arrived later.

Practically, the reliability of gNBs and CN-paths dynamically changes [19] and a certain amount of path setup time is required [18]. Therefore, even if a gNB or CN-path is highly reliable when the allocation begins, it may no longer so after the path setup time. Therefore, NWDAF should estimate the dynamicity of path reliability and path setup time. Then, based on the estimated information, it can assign the paths (i.e., allocate several CN-paths and several gNBs) to the user.

4 | CONSTRAINT MARKOV DECISION PROCESS (CMDP) FORMULATION

We describe a CMDP model for the optimal path allocation by estimating the dynamicity of the reliability of

TABLE 1 Summary of notations

Notation	Description
g	gNB index
$\mathbb{G}$	Set of gNBs
c	CN-path index
$\mathbb{C}$	Set of CN-paths
$\mathbb{C}_g$	Set of CN-paths connected with gNB g
m_{AN}	The maximum number of gNBs that can be simultaneously associated with the user
m_{CN}	The maximum number of core paths that can be simultaneously allocated to the user
$\mathbb{T}$	The set of decision epochs
$\mathbb{S}$	The state space
$\mathbb{R}$	The state space for representing the reliability by gNBs and CN-paths
$\mathbb{R}_{\text{AN},g}$	The state spaces for representing the reliability of gNB g
$r_{\text{AN},g} \in \mathbb{R}_{\text{AN},g}$	The state for representing the reliability of gNB g
$\mathbb{R}_{\mathbf{CN},c}$	The state spaces for representing the reliability of CN-path c
$r_{\mathbf{AN},g} \in \mathbb{R}_{\mathbf{CN},c}$	The state for representing the reliability of CN-path c
$\mathbb{U}$	The state space for representing which gNBs and CN-paths are allocated
$\mathbb{U}_{\mathbf{AN},g}$	The state spaces for representing whether gNB g is allocated or not
$u_{\mathbf{AN},g} \in \mathbb{U}_{\mathbf{AN},g}$	The state for representing whether gNB g is allocated or not
$\mathbb{U}_{\mathbf{CN},c}$	The state spaces for representing whether CN-path c is allocated or not
$u_{\mathbf{CN},c} \in \mathbb{U}_{\mathbf{CN},c}$	The state for representing whether CN-path c is allocated or not
$\mathbb{A}$	The action space
$\mathbb{A}_{\mathbf{AN},g}$	The action spaces for indicating whether gNB g is determined to be allocated or not
$\mathbb{A}_{\mathbf{CN},c}$	The action spaces for indicating whether CN-path c is determined to be allocated or not

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[1] Note that m_{AN} and m_{CN} are determined by the antenna capability of the mobile device and the network operator's policy.

paths and the path setup time, with five elements: (1) decision epoch, (2) state space, (3) action space, (4) transition probability, and (5) cost and constraint functions. Following that, the CMDP model is then transformed into an equivalent linear programming (LP) model to obtain the optimal policy (i.e., stochastic decision). Important notations for the described problem are summarized in Table 1.

4.1 | Decision epoch

NWDAF allocates gNBs and CN-paths to the user at each decision epoch $\mathbb{T} = \{1,2,3,\ldots,T_E\}$, where T_E represents the expected service duration.

4.2 | State space

We define the overall state space $\mathbb{S}$ as

$$\mathbb{S} = \mathbb{R} \times \mathbb{U} \tag{1}$$

where $\mathbb{R}$ is the state space for representing the reliability of gNBs and CN-paths. Also, $\mathbb{U}$ represents the state space for representing which gNBs and CN-paths are allocated to the user. $\mathbb{R}$ is given by

$$\mathbb{R} = \prod_{g \in \mathbb{G}} \mathbb{R}_{\mathrm{AN},g} \times \prod_{c \in \mathbb{C}} \mathbb{R}_{\mathrm{CN},c} \tag{2}$$

where $\mathbb{R}_{\mathrm{AN},g}$ and $\mathbb{R}_{\mathrm{CN},c}$ represent the state spaces for the reliability of gNB g and CN-path c, respectively. In addition, $\mathbb{G}$ and $\mathbb{C}$ are sets including all gNBs and all CN-paths, respectively. Also, $\mathbb{R}_{\mathrm{AN},g}$ and $\mathbb{R}_{\mathrm{CN},c}$ can be denoted by $\{r_{\mathrm{AN}}^{min},\ldots,r_{\mathrm{AN}}^{max}\}$ and $\{r_{\mathrm{CN}}^{min},\ldots,r_{\mathrm{CN}}^{max}\}$, respectively, where r_{AN}^{min} and r_{AN}^{max} represent the lowest and highest reliability of gNBs, respectively. Also, r_{CN}^{min} and r_{CN}^{max} represent the lowest and highest reliability of CN-paths, respectively.

$\mathbb{U}$ can be defined by

$$\mathbb{U} = \prod_{g \in \mathbb{G}} \mathbb{U}_{\mathrm{AN},g} \times \prod_{c \in \mathbb{C}} \mathbb{U}_{\mathrm{CN},c} \tag{3}$$

where $\mathbb{U}_{\mathrm{AN},g}$ and $\mathbb{U}_{\mathrm{CN},c}$ describe the state spaces for representing whether to associate gNB g with the user and to allocate CN-path c to the user or not, respectively. Therefore, $\mathbb{U}_{\mathrm{AN},g}$ and $\mathbb{U}_{\mathrm{CN},c}$ can be defined as $\{0,1\}$. If $u_{\mathrm{AN},g}$ is 1, gNB g is associated with the user. Otherwise, gNB g is not associated with the user. Similarly, $u_{\mathrm{CN},c}$ is 1, CN-path c is allocated to the user. Otherwise, CN-path c is not allocated to the user.

4.3 | Action space

NWDAF determines which gNBs and CN-paths will be assigned to the user. Therefore, the action space $\mathbb{A}$ can be defined as

$$\mathbb{A} = \prod_{g \in \mathbf{G}} \mathbb{A}_{\mathrm{AN},g} \times \prod_{c \in \mathbf{C}} \mathbb{A}_{\mathrm{CN},c} \tag{4}$$

where $\mathbb{A}_{\mathrm{AN},g}$ and $\mathbb{A}_{\mathrm{CN},c}$ are the action spaces for indicating whether gNB g and CN-path c are allocated to the user, respectively. Therefore, $\mathbb{A}_{\mathrm{AN},g}$ and $\mathbb{A}_{\mathrm{CN},c}$ can be represented as $\{0,1\}$. If NWDAF determines that gNB g is associated with the user, $a_{\mathrm{AN},g} = 1$. Otherwise, $a_{\mathrm{AN},g} = 0$. Similarly, if the NWDAF determines that CN-path c should be allocated to the user, $a_{\mathrm{CN},c} = 1$. Otherwise, $a_{\mathrm{CN},c} = 0$.

Meanwhile, since at least one gNB and one CN-path connected with the allocated gNBs must be allocated, the corresponding constraints are defined as follows:

$$\sum_g a_{\mathrm{AN},g} \geq 1 \tag{5}$$

and

$$\sum_c a_{\mathrm{CN},c} \geq 1, c \in \{c | c \in \mathbb{C}_g, a_{\mathrm{AN},g} = 1\} \tag{6}$$

where $\mathbb{C}_g$ represents the set of CN-paths connected with gNB g.

Also, only CN-paths that are connected to the allocated gNBs can be considered as candidates to be allocated. The corresponding constraint can be represented by

$$a_{\mathrm{CN},c} \leq a_{\mathrm{AN},g}, c \in \mathbb{C}_g \tag{7}$$

NWDAF can only allocate a limited number of gNBs and CN-paths due to the mobile device's antenna capability and the network operator's policy. The corresponding constraints are denoted by

$$\sum_g a_{\mathrm{AN},g} \leq m_{\mathrm{AN}} \tag{8}$$

and

$$\sum_c a_{\mathrm{AN},c} \leq m_{\mathrm{CN}} \tag{9}$$

4.4 | Transition Probability

The state $\mathbb{U}$ is influenced by the chosen action $a = \prod_g a_{\mathrm{AN},g} \times \prod_c a_{\mathrm{CN},c}$, and $\mathbb{R}$ and $\mathbb{U}$ are independent.

Thus, with the action a chosen, the transition probability from the current state, $s=[r,u]$, to the next state, $s'=[r',u']$, can be expressed as

$$P[s'|s,a]=P[r'|r]\times P[u'|u,a]. \tag{10}$$

Let $u'_{\mathrm{AN},g},u_{\mathrm{AN},g}$ and $u'_{\mathrm{CN},c},u_{\mathrm{CN},c}$ represent the next, and current states of $\mathbb{U}_{\mathrm{AN},g}$ and $\mathbb{U}_{\mathrm{CN},c}$, respectively. Then, since NWDAF can independently allocate CN-paths and gNBs, the transition probability of u is given by (11) at the top of the next page.

$$\begin{aligned}P[u'|u,a]=&\prod_{g\in\mathbb{G}}P[u'_{\mathrm{AN},g}|u_{\mathrm{AN},g},a_{\mathrm{AN},g}]\\&\times\prod_{c\in\mathbb{C}}P[u'_{\mathrm{CN},c}|u_{\mathrm{CN},c},a_{\mathrm{CN},c}]\end{aligned} \tag{11}$$

To allocate paths in the mobile network, the corresponding signaling procedure is required [2]. That is, a certain amount of path setup time is needed, which is heavily influenced by the transmission delay between network functions (i.e., NWDAF, SMF, AMF, and UPF). Note that the transmission delay varies dynamically according to the network conditions. Thus, the path setup times of gNBs and CN-paths can be assumed to be random variables following exponential distributions with mean $1/\lambda_{\mathrm{AN}}$ and mean $1/\lambda_{\mathrm{CN}}$, respectively [20]. Then, the probabilities that gNB and CN-path are allocated at the next decision epoch can be calculated as $\lambda_{\mathrm{AN}}\tau$ and $\lambda_{\mathrm{CN}}\tau$, where τ is the duration between decision epochs, respectively [20]. Therefore, the corresponding transition probabilities of $\mathbb{U}$ can be represented as (12) and (13) on the following page.

$$\begin{aligned}&P[u'_{\mathrm{AN},g}|u_{\mathrm{AN},g},a_{\mathrm{AN},g}\neq u_{\mathrm{AN},g}]\\&=\begin{cases}\lambda_{\mathrm{AN}}\tau, & \text{if } u'_{\mathrm{AN},g}=a_{\mathrm{AN},g}\\1-\lambda_{\mathrm{AN}}\tau, & \text{if } u'_{\mathrm{AN},g}=u_{\mathrm{AN},g}\\0, & \text{otherwise,}\end{cases}\end{aligned} \tag{12}$$

$$\begin{aligned}&P[u'_{\mathrm{CN},c}|u_{\mathrm{CN},c},a_{\mathrm{CN},c}\neq u_{\mathrm{CN},c}]\\&=\begin{cases}\lambda_{\mathrm{CN}}\tau, & \text{if } u'_{\mathrm{CN},c}=a_{\mathrm{CN},c}\\1-\lambda_{\mathrm{CN}}\tau, & \text{if } u'_{\mathrm{CN},c}=u_{\mathrm{CN},c}\\0, & \text{otherwise,}\end{cases}\end{aligned} \tag{13}$$

Meanwhile, when NWDAF does not change the allocated gNBs and CN-paths, no signaling procedure is required (i.e., path setup time is not consumed). Therefore, the next u state of gNBs and CN-paths is always equal to their current u state of them.

4.5 | Cost and constraint functions

One of the aims of the CMDP model is to reduce network costs. Therefore, we define the cost function $O(s,a)$ on the network cost, which is denoted as

$$O(s,a)=\sum_g\omega_{\mathrm{AN},g}u_{\mathrm{AN},g}+\sum_c\omega_{\mathrm{CN},c}u_{\mathrm{CN},c} \tag{14}$$

where $\omega_{\mathrm{AN},g}$ and $\omega_{\mathrm{CN},c}$ are the network cost weighs on gNB g and CN-path c, respectively.

Meanwhile, another objective is to ensure the required reliability. Therefore, we define the constraint function $R(s,a)$ on the reliability. Note that reliability can be defined as the probability that at least one packet is delivered without any error or loss. The access network (i.e., the allocated gNBs) should receive at least one packet from any allocated CN-paths and transmit it to the user without any error or loss for reliable transmission. Let $R_{\mathrm{CA},g}(s,a)$ and $R_{\mathrm{AN},g}(s,a)$ denote the probability that gNB g receives the packet from the core network (i.e., through any allocated CN-paths) and the probability that gNB g transmits the packet to the user without any error or loss, respectively. Then, the probability that all allocated gNBs fail to receive or transmit the packet without any error or loss is calculated as $\prod_{g\in\mathbf{G}}\{1-R_{\mathrm{AN},g}(s,a)R_{\mathrm{CA},g}(s,a)\}$. Therefore, $R(s,a)$ can be obtained as

$$R(s,a)=1-\prod_{g\in\mathbf{G}}\{1-R_{\mathrm{AN},g}(s,a)R_{\mathrm{CA},g}(s,a)\}. \tag{15}$$

Since $r_{\mathrm{AN},g}$ represents the reliability of gNB g (i.e., the probability that gNB g will transmit the packet to the user without any error or loss) and $u_{\mathrm{AN},g}$ denotes whether gNB g is allocated to the user or not, $R_{\mathrm{AN},g}(s,a)$ can be defined as

$$R_{\mathrm{AN},g}(s,a)=r_{\mathrm{AN},g}u_{\mathrm{AN},g}. \tag{16}$$

Meanwhile, because $r_{\mathrm{CN},c}$ represents the reliability of CN-path c (i.e., the probability that CN-path c transmits the packet to the user without any error or loss) and $u_{\mathrm{CN},c}$ denotes whether CN-path c is allocated to the user or not, the probability that all allocated CN-paths fail to transmit the packet to gNB g without any error or loss can be calculated as $\prod_{c\in\mathbb{C}_g}(1-r_{\mathrm{CN},c}u_{\mathrm{CN},c})$. Then, $R_{\mathrm{CN},g}(s,a)$ is defined as

$$R_{\mathrm{CA},g}(s,a)=1-\prod_{c\in\mathbb{C}_g}(1-r_{\mathrm{CN},c}u_{\mathrm{CN},c}). \tag{17}$$

4.6 | Optimization formulation

The average network cost and the average reliability, ζ_O and ζ_R, can be defined as

$$\zeta_O=\limsup_{t\rightarrow}\frac{1}{t}\sum_{t'}^{t}\mathrm{E}[O(s_{t'},\ a_{t'})] \tag{18}$$

and

$$\zeta_R=\limsup_{t\rightarrow}\frac{1}{t}\sum_{t'}^{t}\mathrm{E}[R(s_{t'},\ a_{t'})] \tag{19}$$

where $s_{t'}$ and $a_{t'}$ represent the state and the chosen action at the decision epoch t', respectively.

Then, the CMDP model can be expressed as

$$\min_{\pi}\zeta_0 \tag{20}$$

$$\text{s.t. }\zeta_R\geq\theta_R \tag{21}$$

where θ_R represents the required reliability of the user.

The CMDP model mentioned above can be transformed into an equivalent LP model [17]. When $\phi(s,a)$ represents the stationary probability of state s and action a, the equivalent LP model is expressed as follows:

$$\min_{\phi(s,a)}\sum_{s}\sum_{a}\phi(s,a)O(s,a) \tag{22}$$

$$\text{s.t. }\ \sum_{s}\sum_{a}\phi(s,a)R(s,a)\geq\theta_R \tag{23}$$

$$\sum_{a}\phi(s',a)=\sum_{s}\sum_{a}\phi(s,a)P[s'|s,a],s'\in\mathbf{S} \tag{24}$$

$$\sum_{s}\sum_{a}\phi(s,a)=1 \tag{25}$$

$$\phi(s,a)\geq 0 \tag{26}$$

The goal of (22) is to minimize the average network cost. The constraint for ensuring the required reliability of the user θ_R on the other hand is expressed in (23). Meanwhile, the constraint in (24) satisfies the Chapman–Kolmogorov equation. The constraints in (25) and (26) are defined for the probability properties.

The solution of the CMDP model (i.e., the optimal policy), $\pi^*(s,a)$, which is the probability of taking a particular action a at a certain state s, can be obtained from the solution of the LP model above

$$\pi^*(s,a)=\frac{\phi^*(s,a)}{\sum_{a'}\phi^*(s,a')}\quad\text{for } s\quad\mathbb{S},\sum_{a'}\phi^*(s,a')>0 \tag{27}$$

4.7 | RG-MAA

To find the stochastic optimal policy, $\pi^*(s,a)$, NWDAF first analyzes the historical packet error rate and path setup time to transition probability, cost function, and constraint function. NWDAF describes the LP model and finds the optimal stationary probability $\phi^*(s,a)$ based on the transition probability, cost function, and constraint functions. Finally, NWDAF obtains the stochastic optimal policy $\pi^*(s,a)$ from the optimal stationary probability, as in (27).

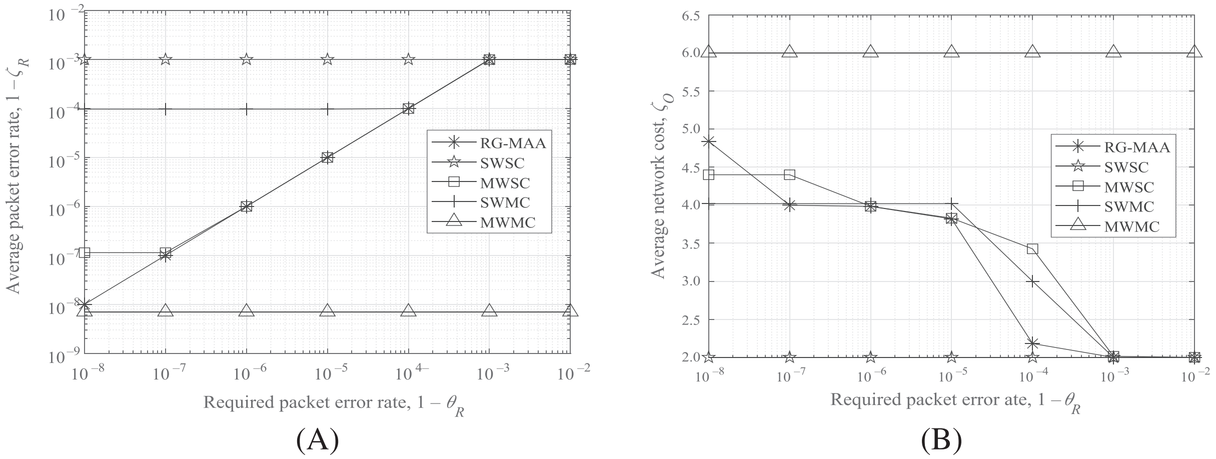
NWDAF uses the stochastic optimal policy $\pi^*(s,a)$, to determine the current action a_t periodically (Algorithm 1). NWDAF specifically checks the current states of the reliability r_t and path status u_t at each time t (line 3 in Algorithm 1). Based on the current state $s_t=(r_t,s_t)$, NWDAF chooses the action a_t based on the optimal stationary probability $\pi^*(s,a)$ (line 4 in Algorithm 1). According to the action selected, NWDAF initiates the path setup procedure with SMF and AMF to allocate the determined gNBs and CN-paths (line 5 in Algorithm 1).

5 | EVALUATION RESULT

We develop an event-driven simulator for performance evaluation. The following describes the evaluation environment. Four gNBs are installed, and nine CN-paths are constructed. Each gNB is connected with one to four distinct CN-paths. From the average path setup times [18], both $1/\lambda_{\mathrm{AN}}$ and $1/\lambda_{\mathrm{CN}}$ are set to 0.7. The maximum number of allocated CN-paths and gNBs, m_{AN} and m_{CN}, are set to 2 and 4, respectively. Additionally, we set the reliability range as $[0.99,0.99999999]$ [5] and the reliability of

ALGORITHM 1 RG-MAA Obtain the stochastic optimal policy $\pi^*(s,\ a)$ from (27)

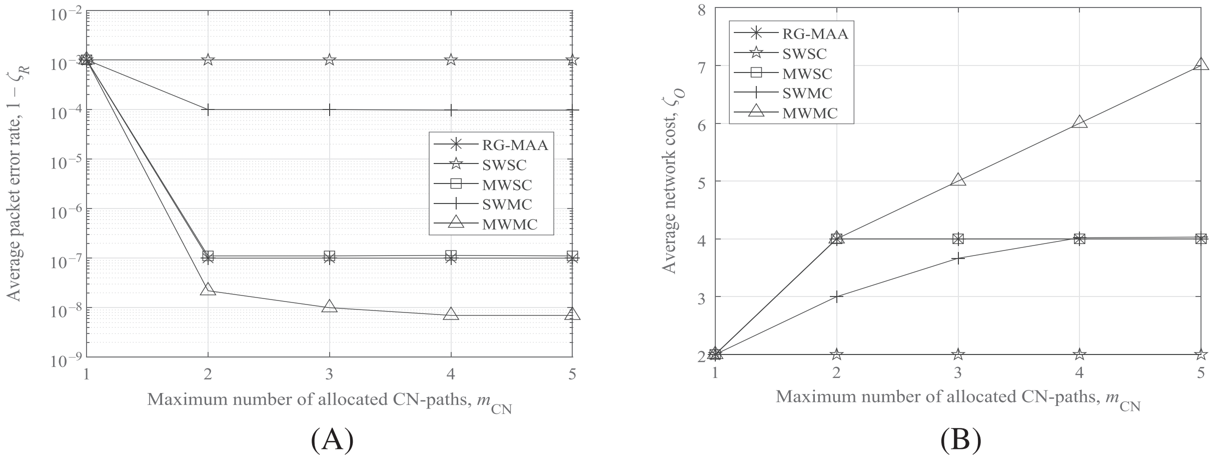
```
for $t$ do
    Check the current states, $r_t$ and $u_t$
    Choose $a_t$ based on $\pi^*(s,\ a)$
    Trigger the path setup procedure according to $a_t$
end for
```



(A)

(B)

FIGURE 2 Effect of the required packet error rate, $1-\theta_R$: (A) Average packet error rate, 1-ζ_R and (B) Average network cost, ζ_O



(A)

(B)

FIGURE 3 Effect of maxim number of allocated CN-paths, $m_{\mathbf{CN}}$: (A) Average packet error rate, 1-ζ_R and (B) Average network cost, ζ_O

each gNB and CN-paths, $r_{\mathrm{AN},g}$ and $r_{\mathrm{CN},p}$ is set to a random value within a specific range at each time. We set $\omega_{\mathrm{AN},g}$ and $\omega_{\mathrm{CN},c}$ as $1/r_{\mathrm{AN},g}$ and $1/r_{\mathrm{CN},c}$, respectively [12]. The default required reliability, θ_R, is defined by 0.9999999. Note that the difference in performance (i.e., average network cost and average reliability) calculated from the closed form solution $\pi^*(s,a)$ and that calculated from the event-driven simulator is significant, that is, 0%–0.000098%.

We compare the proposed scheme, RG-MAA, to the following four schemes: (1) SWSC that allocates one gNB and one CN-path, (2) MWSC that allocates several gNBs less than or equal to m_{AN} and one CN-path [8], (3) SWMC that allocate one gNB and several CN-paths less than or equal to m_{CN} [12], and (4) MWMC that allocates m_{AN} gNBs and m_{CN} CN-paths. For a fair comparison, all comparison schemes allocate the optimal gNBs and CN-paths to provide minimum network cost while ensuring the required reliability by considering the path setup time and dynamicity of the reliability of gNBs and CN-paths.[2]

5.1 | Effect of $1-\theta_R$

Figure 2A,B shows the effect of the required packet error rate $1-\theta_R$ on the average packet error rate $1-\zeta_R$ and the average network cost ζ_O, respectively.[3] From Figure 2A, it can be found that RG-MAA always maintains the average packet error rate $1-\zeta_R$ below the required one $1-\theta_R$. This is because RG-MMA adaptively changes or allocates new gNBs or CN-paths that are expected to have

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[2] If the required reliability cannot be guaranteed, all comparison schemes selects gNBs and CN-paths with the highest reliability possible.

[3] Note that ζ_R and θ_R represent the average reliability of mobile network and the required reliability.

higher reliability after the path setup time. However, this adaptive operation can also increase the network cost ζ_O as well (see Figure 2B).

Meanwhile, from Figure 2A, it can be shown that some comparison schemes (i.e., SWSC, SWMC, and MWSC) cannot maintain the average packet error rate $1-\zeta_R$ below the required one $1-\theta_R$. This is because they do not provide sufficient gNBs or CN-paths. Furthermore, it can be shown that $1-\zeta_R$ of MWMC is much lower than the required one. This indicates that MWMC allocates unnecessary gNBs and CN-paths, resulting in higher network costs ζ_O (see Figure 2B).

5.2 | Effect of $m_{\mathbf{CN}}$

Figure 3A,B shows the effect of the maximum number of allocated CN-paths, $m_{\mathbf{CN}}$, on the average packet error rate $1-\zeta_R$ and the average network cost ζ_O, respectively. As shown in Figure 3A,B, RG-MAA has the lowest ζ_O among the comparison schemes guaranteeing θ_R (i.e., MWMC and RG-MAA) regardless of $m_{\mathbf{CN}}$. This is because RG-MAA always allocates the correct number of gNBs and CN-paths regardless of $m_{\mathbf{CN}}$ (i.e., excessive numbers of gNBs and CN-paths are not allocated). However, because MWMC allocates more numbers of gNBs or CN-paths than are required, their network costs are higher than those of RG-MAA.

6 | CONCLUSION

To ensure the required reliability while minimizing the network costs due to redundant transmission, we propose RG-MAA, which allocates appropriate paths by estimating the path setup time and path reliability dynamicity. We devised an optimization problem to obtain the optimal policy using a CMDP. The evaluation results showed that RG-MAA significantly reduces network costs while ensuring the required reliability. Furthermore, it has been found that RG-MAA adapts the number of allocated gNBs and CN-paths based on the operating environment (e.g., required reliability). In our future works, we will extend RG-MAA to learn the dynamicity of the reliability of paths using a reinforcement learning method.

CONFLICT OF INTEREST

The authors declare that there are no conflicts of interest.

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