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A New Lossless Fault-Tolerance Mechanism in Hybrid Wireless-Optical Broadband Access Network

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ABSTRACT With the tremendous growth of the traffic demand of emerging 5G applications, the survivability has become more significant in the wireless-optical broadband access network (WOBAN), since any failure of the network components could interrupt a large amount of traffic. A large amount of data could be lost even if there is a very short interruption. Previous works focus on finding the alternate paths or deploying backup fiber to recover the interrupted traffic. However, these works encounter three potential problems. First, the deployment of a backup fiber could increase the cost of recovery. Second, they must reroute the interrupted traffic to the backup resources, which could cause a long recovery time. Third, a large number of network packets could be lost during the recovery processes. To address these problems, a lossless fault-tolerance mechanism combining with parallel routing and network coding (LFTM-PR-NC) is proposed in this paper to enhance the survivability of WOBAN against any optical network unit-level and wireless-level failures. Numerical results show that the proposed LFTM-PR-NC mechanism significantly outperforms the previous mechanism. Meanwhile, the LFTM-PR-NC mechanism could dramatically decrease the recovery time when a failure occurs.

INDEX TERMS Parallel routing, network coding, survivability, hybrid wireless-optical broadband access network (WOBAN).

I. INTRODUCTION

With the increasing popularity of intelligent terminal equipment, a variety of mobile applications and multimedia services continue to exploit. Particularly, with the fast development of the fifth generation (5G) technologies, which is commonly forecasted to be deployed around 2020, an enormous number of devices could connect to the networks [1]. The tremendous mobile data could be produced by the various emerging 5G applications such as Internet of things (IoT) [2]–[4], smart grid [5], smart community [6] and so on. It is estimated that the number of IoT devices will reach between 20 and 46 billion by 2020 [7]. Furthermore, the requirements of 5G network aim to support 1 million devices per square kilometers [8]. With the tremendous growth of data generated by 5G applications, a high-capacity, low-latency, reliable and ubiquitous coverage access network is required to connect and control the large number of devices [9]. However, the traditional network access methods have limitations to meet the growing requirements. To overcome the limitations, a hybrid network called wireless-optical broadband access network (WOBAN), which captures the advantages of both optical and wireless networks, is considered one of the best and most efficient access solutions in the future [10]–[12] and is regarded as a cost-efficient infrastructure to enable the wide range of emerging 5G applications [13]–[15].

The wireless part of WOBAN captures the characteristics of low cost, easy deployment, and flexibility. The optical part of WOBAN has the characteristics of high bandwidth, low loss and reliability. As the hybrid networks that combined these two parts, the WOBAN can provide ubiquitous access, faster and more efficient services for the end users [16]. However, with the explosive growth of the diverse traffic and the expansion of the coverage area which result in an enhancement in the number of end users, humongous packages could be lost when any network component fails. Therefore, the problem of survivability is more important in WOBAN [17]–[19].

Most of the related research works focus on finding the alternate paths or deploying backup fiber to recover the interrupted traffic when any of the network components fail. The first category research is taking the advantage of the self-healing ability in wireless networks, since they have the alternative paths in wireless networks. The interrupted traffic can be rerouted to the alternative paths. The failures of distribution fiber (DF), optical network units (ONU), wireless links and wireless routers can be healed by these technologies. A cost-efficient protection mechanism called wireless rerouting with backup radios is proposed in [20] to cope with the failure of distribution fiber. Each ONU is allocated the backup ONUs. The residual capacity is reserved by the backup ONUs for the primary ONU. The wireless backup path, which is composed of several wireless links, is also reserved to reroute the failed traffic from primary ONU to its backup ONUs. The mechanism called risk-and-delay-aware routing (RADAR) is presented in [21] to make WOBAN fault tolerant and self-healing with minimal service disruption. The link state information and risk lists are employed to explore the delay awareness and fault tolerance routing mechanism. The authors in [22] propose a capacity and delay-aware routing (CaDAR) algorithm to reduce the network-wide average packet delay in the wireless and optical part of WOBAN. The optimal capacity assignment on the links and delay-aware routing are considered to design the efficient routing mechanism.

The additional backup resources, such as backup fiber and backup wireless transceiver, are employed to reroute the interrupted traffic in the other research since the optical part of WOBAN lacks survivability to cope with any failure due to its tree topology. The failures of optical line terminal (OLT), feeder fiber (FF), optical splitter, distribution fiber (DF), optical network units (ONU), wireless links and wireless routers can be healed by these technologies. In this scenario, multiple WOBANs are employed to deal with the OLT-level failures, since the backup fiber are often deployed between the backup ONUs in different WOBANs. Each WOBAN is called a segment. The maximum protection with minimum cost problem is solved by means of finding the maximum flow of minimal cost in [23]. A protection mechanism, which randomly selecting the backup ONUs in the neighbor segments and deploying additional backup fiber between the backup ONUs, is proposed in this paper. The issues of selecting backup ONUs and deploying backup fiber are defined as the minimum recovery cost problem and the maximum-protection-minimum cost with remote backup segment problem and the problems are formulated to the integer linear programming (ILP) in [24]. Furthermore, the simulated annealing (SA) algorithm is employed to select the optimal backup ONUs and an enhanced greedy cost-efficiency algorithm is proposed to optimize the deployment of backup fibers. An efficient protection scheme called cluster-based protection is presented to recover traffic when multiple segments fail in [25]. Several segments are clustering into a cluster to reduce the overhead for the traffic recovery. An ILP model and a heuristic approach are presented to minimize the deployment cost of backup fibers.

The redundant backup resources are not considered in some of the previous research. However, the failure detection and rerouting which spend a long recovery time are needed to recover the traffic in these researches when a failure occurs. On the contrary, the redundant backup cost for deploying the dedicated backup resources is considered in other research. A shorter path switching time is also required in the research. However, a large amount of traffic could still be lost even during a very short interruption. Therefore, the efficient method that reduces the backup cost and recovery time should be significantly investigated.

In order to address these problems, a lossless fault-tolerance mechanism combining with parallel routing and network coding (LFTM-PR-NC) is proposed in this paper for low cost, rapid and lossless recovery. First, the number of routing paths and the parallel routing is calculated according to the reliability of traffic requirement and the delay of wireless and optical links. Then the original packets are coded to encoded packets according to the optimal number of encoded packets which could result in the minimum cost of recovery. Finally, the encoded packets are sent to the destination node according to the packets allocation scheme which could result in the minimum number of encoded packets on recovering. The proposed LFTM-PR-NC mechanism can recover interrupted traffic rapidly without loss of packets by means of combining parallel routing and network coding when a failure occurs. The failure is tolerated by the redundant encoded packets. Furthermore, since the network coding combines multiple original packets into an encoded packet and the redundant encoded packets being employed in the coding process, the loss of the encoded packet does not mean the loss of original packets. In fact all the original packets can be recovered when the destination node receives enough encoded packets.

This paper is a significant extension of our conference paper [26]. The improvement of this paper as follows.

- The queue length of WONUs is estimated by queue theory to reflect the real state of WONUs.
- We prove and find out the optimal data packet allocation scheme.
- The optimal number of encoded packets is derived in the coding process.
- The redundant encoded packets are analyzed.

The rest of this paper is organized as follows: The network model and the principle of the proposed mechanism is explained in section II. In section III, we analyze the delay in wireless network and optical network. In section IV, the proposed LFTM-PR-NC mechanism is presented. In section V, the numerical results of LFTM-PR-NC mechanism is introduced. Finally, we conclude the paper in section VI.

II. NETWORK MODEL

A. NETWORK ARCHITECTURES

The architecture of WOBAN is shown in Fig. 1. The WOBAN is composed of a wireless mesh networks (WMN) located in the front-end and a passive optical network (PON) located in the back-end. The end users are ubiquitously accessed to WOBAN via wireless routers in the WMN. The traffic in WMN are converged to PON and are delivered to the Internet. In the back-end PON, each ONU are equipped with a wireless transceiver function. These ONUs are called wireless ONUs (WONUs). The WONU is a gateway that correlates the PON and WMN and it serves as an interface between the wired and wireless domain. Each WOBAN consists of a unique OLT, several WONU and a large number of wireless routers. Several OLTs which belong to different WOBANs are located in the telecom central office (CO) [20]–[22].

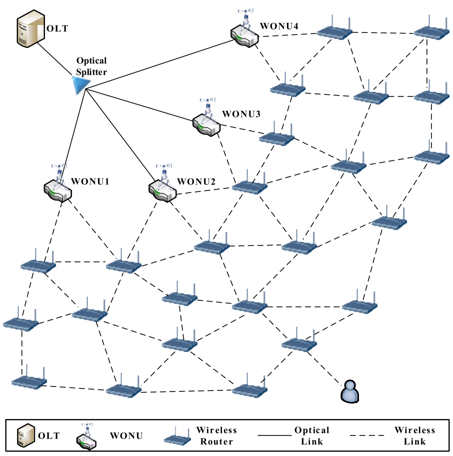

FIGURE 1. The WOBAN architectures.

B. NETWORK FAILURES

The failures in WOBAN can be divided in to three categories:

- **OLT-level failures:** the failures of OLT, FF and optical splitter.
- **ONU-level failures:** the failures of DF and WONU.
- **Wireless-level failures:** the failures of wireless routers and wireless links.

Since all the packets cannot be sent to the OLT in the OLT-level failures scenario, all the traffic in the failed WOBAN could be interrupted. In the ONU-level failures scenario, only the traffic passing through the failed components could be interrupted. The WOBAN can still provide service to the end users in this scenario. In the wireless-level failures scenario, the traffic passing the failed wireless router or wireless link can be interrupted.

The OLT-level failures cannot be healed in a single WOBAN due to the unique tree structure of PON. The redundant backup fibers which are connected with the different WOBANs are needed to deal with the OLT-level failures. Therefore, only the ONU-level failures and wireless-level failures are considered in this paper.

C. THE PRINCIPLE OF LFTM-PR-NC MECHANISM

According to combining network coding and parallel routing, the proposed LFTM-PR-NC mechanism can achieve rapid and lossless recovery when the ONU-level failures or the wireless-level failures occur. Furthermore, the load balancing and eliminating retransmission are achieved when the WOBAN is working. The principle of LFTM-PR-NC mechanism is shown in Fig. 2.

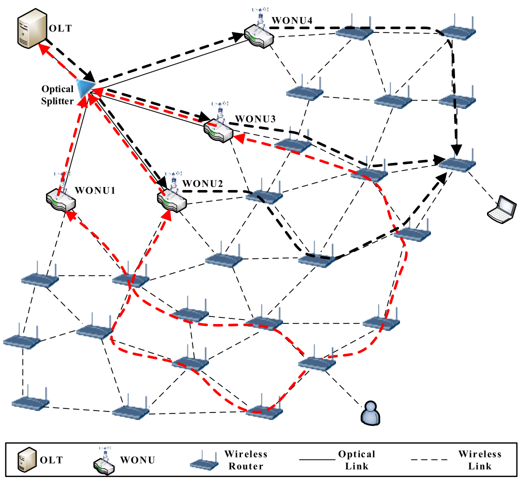

FIGURE 2. The principle of LFTM-PR-NC Mechanism.

In the upstream transmission, the wireless router calculates N WONU-disjoint parallel routing paths that meet the requirement of the traffic. Then the wireless router groups the packets, each group has m packets. Moreover, the m packets in each group are coded into M encoded packets by the wireless router. Finally, according to the packet allocation scheme, the encoded packets are sent to the OLT through N WONU-disjoint parallel routing paths. If any one path is interrupted which is caused by a ONU-level failure or wireless-level failure, the OLT only needs to receive m linearly independent encoded packets from other N-1 routing paths to decode the packets.

In the downstream transmission, as well as the upstream transmission, the OLT encodes the m original packets to M encoded packets. And the M encoded packets are sent to the accessing wireless router of the end user by means of the N WONU-disjoint parallel routing paths.

Since the principle of upstream transmission and downstream transmission is similar, the upstream transmission is considered to explain the principle in this paper.

III. DELAY ANALYSIS

Each routing path in WOBAN has two parts. The one is the delay in optical links, we call it back-end delay, since the optical network is located on the back-end of WOBAN.

The other one is the delay in wireless links. We call it front-end delay. Since the wireless network is located on the front-end of WOBAN. Therefore, the delay in each routing path is comprised of front-end delay and back-end delay.

A. FRONT-END DELAY

The front-end delay is caused by the several hops routing path from end users to WONU or the opposite direction in WMN.

Assume that the time division multiple access scheme is employed in the WMN. The delay on each wireless link include four parts: transmission delay, slot-synchronization, queuing delay and propagation delay. The delay on the wireless link u-v between adjacent node u and v is described in (1) [22].

$$d_{uv} = \frac{1}{2\mu C_{uv}} + \frac{1}{\mu C_{uv} - \lambda_{uv}} \tag{1}$$

Where $1/\mu$ is the average packet size, C_{uv} is the capacity on wireless link *u-v* and λ_{uv} is the packet density on wireless link *u-v*.

Then the total front-end delay on a routing path can be calculated in (2). Where **S** is the set of wireless links which is belong to a routing path.

$$D_{TOTAL}^{W} = \sum d_{ij}, \quad if\ link\ i-j\ belong\ to\ \mathbf{S} \tag{2}$$

B. BACK-END DELAY

The back-end delay is caused by queuing in the WONU (upstream) or OLT (downstream) and scheduling according to dynamic bandwidth allocation (DBA) algorithm in PON. The WONU converges the traffic packets from WMN and utilizes the DBA algorithm to deliver the packets from WONUs to OLT or the opposite direction. The DBA algorithm called interleaved polling with adaptive cycle time (IPACT) [27] is applied in LFTM-PR-NC mechanism.

1) UPSTREAM TRANSMISSION

In the upstream transmission, all the WONU share the upstream channel by means of time division multiplexing. Each WONU can only send upstream packets and request messages within the time slot which is authorized by the OLT. The request messages contain the queue length of the WONU, indicating the amount of bandwidth that the WONU expects to send in the next polling cycle. The grant messages include the authorized time slot to the WONU. Suppose that the first input first output (FIFO) algorithm is employed to schedule the queue. When a packet arrived at a WONU, the interactive process between WONU and OLT is shown in Fig. 3.

The total back-end delay, which is the time from a packet arrives at WONU to the OLT receives the packet, is calculated in (3).

$$D_{TOTAL}^{UP} = d_R + d_G + d_S + d_Q + d_P \tag{3}$$

Where d_R is the time interval from the packet arrives at WONU until the next request message sent by that WONU.

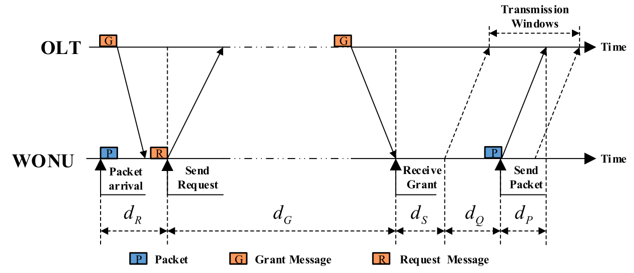

FIGURE 3. The interactive process between WONU and OLT.

It can be calculated in (4) on average [27]. Where T_{cycle} is the length of polling cycle.

$$E\left[d_R\right] = E\left[T_{cycle}\right]/2 \tag{4}$$

d_G is the time interval from when WONU sends request message until when the WONU receives grant message from OLT. The WONU could send request message to apply the transmission bandwidth for the arrived packet. Then the OLT could authorize appropriate bandwidth to the WONU and send a grant message to the WONU. Since the grant bandwidth is often less than the bandwidth that the WONU expect to send, d_G may contains multiple polling cycles. Suppose that q is the queue size when the packet arrives at WONU, W_{MAX} is the maximal grant bandwidth of a WONU in a polling cycle, $W_P^{[i]}$ is the grant bandwidth which is requested before the packet arrived. d_G can be calculated in (5) [27].

$$E\left[d_G\right] = \begin{cases} 0, & if\ q \le E\left[W_P^{[i]}\right] \\ E\left[T_{cycle}\right] \times \left\lceil \frac{q - E\left[W_P^{[i]}\right]}{W_{MAX}} \right\rceil, & if\ q > E\left[W_P^{[i]}\right] \end{cases} \tag{5}$$

d_S is the time interval from when the first grant message arrives at WONU until the beginning of the first authorized time slot. d_S can be neglected compared to the other components.

d_Q is the queue delay from the beginning of the authorized time slot until the packet is sent by the WONU. d_Q is shown in (6) [27]. Where R_O is the transmission rate in optical fiber.

$$E\left[d_Q\right] = \begin{cases} \frac{q}{R_O}, & if\ q \le E\left[W_P^{[i]}\right] \\ \frac{\left(q - E\left[W_P^{[i]}\right]\right) \bmod W_{MAX}}{R_O}, & if\ q > E\left[W_P^{[i]}\right] \end{cases} \tag{6}$$

d_P is the propagation delay that the packet propagates in the optical fiber as shown in (7). Where *RTT* is the round-trip time of the WONU.

$$E\left[d_P\right] = RTT/2 \tag{7}$$

TABLE 1. Notion defined.

Symbol	Definition
λ_i	the packet intensity of $WONU_i$
$1/\mu$	the average length of packets
$W_i(k)$	the grant bandwidth of $WONU_i$ in the grant message during the kth polling cycle
$V_i(k)$	the bandwidth that $WONU_i$ applies to the OLT in the request message during the kth polling cycle
$N_i(T)$	the number of packets arriving by $WONU_i$ during time T
$T^i_{cycle}(k)$	the length of the kth polling cycle for $WONU_i$

Then the total back-end delay is shown in (8).

$$D^{UP}_{TOTAL} = \begin{cases} \dfrac{E\left[T_{cycle}\right]}{2} + \dfrac{q}{R_O} + \dfrac{RTT}{2}, \\ \quad if\ q \le E\left[W^{[i]}_P\right] \\ \dfrac{E\left[T_{cycle}\right]}{2} + E\left[T_{cycle}\right] \times \left\lceil \dfrac{q - E\left[W^{[i]}_P\right]}{W_{MAX}} \right\rceil, \\ \quad if\ q > E\left[W^{[i]}_P\right] \\ + \dfrac{(q - E\left[W^{[i]}_P\right]) \bmod W_{MAX}}{R_O} + \dfrac{RTT}{2} \end{cases} \tag{8}$$

However, $E\left[T_{cycle}\right]$ and $E\left[W^{[i]}_P\right]$ are still unknown in (8). If we can get these two parameters, then the total back-end delay of upstream transmission can be obtained.

Assume that the arrival of packets in WONU follows the Poisson distribution. The bandwidth requested to the OLT in the kth polling cycle depends on the number of packets arrived in the previous polling cycle. The following notion are defined in this paper.

The probability that the number of packets arrived at $WONU_i$ during the kth polling cycle is equal to n is shown in (9).

$$P\left\{N_i(T^i_{cycle}(k)) = n\right\} = \frac{(\lambda_i T^i_{cycle}(k))^n}{n!} e^{-\lambda_i T^i_{cycle}(k)} \tag{9}$$

The mean value of the number of arriving packets for $WONU_i$ in the kth polling cycle is shown in (10).

$$E\left[N_i(T^i_{cycle}(k))\right] = \lambda_i E\left[T^i_{cycle}(k)\right] \tag{10}$$

The bandwidth requested by $WONU_i$ to the OLT in the $k+1$th polling cycle is shown in (11).

$$E\left[V_i(k+1)\right] = \frac{1}{\mu} E\left[N_i(T^i_{cycle}(k))\right] = \frac{\lambda_i}{\mu} E\left[T^i_{cycle}(k)\right] \tag{11}$$

According to $E\left[V_i(k+1)\right]$, all the WONU can be divided to two categories: high load WONU (HL-WONU) and low load WONU (LL-WONU)

- If a WONU belongs to HL-WONU, then the requested bandwidth of the WONU satisfied $E\left[V_i(k+1)\right] > W_{MAX}$.
- If a WONU belongs to LL-WONU, then the requested bandwidth of the WONU satisfied $E\left[V_i(k+1)\right] \le W_{MAX}$.

a: IF **HL-WONU** $= \emptyset$ *AND* **LL-WONU** $\neq \emptyset$

That means all the requested bandwidth of WONUs satisfied $E\left[V_i(k+1)\right] \le W_{MAX}$. Then the grant bandwidth in the $k+2$th polling cycle must be equal to the requested bandwidth in the $k+1$th polling cycle as shown in (12).

$$E\left[W_i(k+2)\right] = E\left[V_i(k+1)\right] \tag{12}$$

The length of the $k+2$th polling cycle can be calculated in (13), where K is the number of WONUs in WOBAN, T_g is the protection time slot.

$$\begin{aligned} E\left[T^i_{cycle}(k+2)\right] &= \sum_{i=1}^{K} E\left[W_i(k+2)\right] + KT_g \\ &= \sum_{i=1}^{K} \frac{\lambda_i}{\mu} E\left[T^i_{cycle}(k)\right] + KT_g \end{aligned} \tag{13}$$

In the steady state, the mean length of different polling cycles should be equal as shown in (14).

$$E\left[T^i_{cycle}(k)\right] = E\left[T^i_{cycle}(k+1)\right] = \cdots = E\left[T_{cycle}\right] \tag{14}$$

Then we can obtain the mean length of polling cycle in (15).

$$E\left[T_{cycle}\right] = \frac{KT_g}{1 - \frac{1}{\mu}\sum_{i=1}^{K}\lambda_i} \tag{15}$$

b: IF **HL-WONU** $\neq \emptyset$ *AND* **LL-WONU** $\neq \emptyset$

The grant bandwidth in the $k+2$th polling cycle is described in (16).

$$E\left[W_i(k+2)\right] = \begin{cases} E\left[V_i(k+1)\right], & if\ WONU_i \in \textbf{LL-WONU} \\ W_{MAX}, & if\ WONU_i \in \textbf{HL-WONU} \end{cases} \tag{16}$$

Then the length of the $k+2$th polling cycle can be calculated in (17).

$$\begin{aligned} E\left[T^i_{cycle}(k+2)\right] &= \sum_{i=1}^{K} E\left[W_i(k+2)\right] + KT_g \\ &= \sum_{v_i \in \textbf{LL-WONU}} \frac{\lambda_i}{\mu} E\left[T^i_{cycle}(k)\right] \\ &\quad + \sum_{v_i \in \textbf{HL-WONU}} W_{MAX} + KT_g \end{aligned} \tag{17}$$

Similarly, the mean length of polling cycle is described in (18). Where $|\textbf{HL}|$ represents the number of WONUs in **HL-WONU**.

$$E\left[T_{cycle}\right] = \frac{W_{MAX} \times |\mathbf{HL}| + KT_g}{1 - \frac{1}{\mu}\sum\limits_{v_i \in \mathbf{LL\text{-}WONU}} \lambda_i} \tag{18}$$

c: IF **HL-WONU** $\neq \emptyset$ *AND* **LL-WONU** $= \emptyset$

That means all the requested bandwidth of WONUs satisfied $E\left[V_i(k+1)\right] > W_{MAX}$. All the WONUs must be granted the maximum bandwidth as shown in (19).

$$E\left[W_i(k+2)\right] = W_{MAX} \tag{19}$$

Similarly, the mean length of polling cycle is described in (20).

$$E\left[T_{cycle}\right] = \sum_{\mathrm{i}=1}^{K} W_{MAX}+KT_g = K(W_{MAX} + T_g) \tag{20}$$

In summary, the mean length of polling cycle $E\left[T_{cycle}\right]$ is shown in (21), as shown at the bottom of this page.

Then the grant bandwidth of a WONU is described in (22).

$$E\left[W_P^{[i]}\right] = \begin{cases} \frac{\lambda_i}{\mu} E\left[T_{cycle}\right] & \text{if } WONU_i \in \mathbf{LL\text{-}WONU} \\ W_{MAX}, & \text{if } WONU_i \in \mathbf{HL\text{-}WONU} \end{cases} \tag{22}$$

Therefore, the total back-end delay of upstream transmission can be obtained according to (8), (21) and (22).

2) DOWNSTREAM TRANSMISSION

In the downstream transmission, OLT would choose a target WONU for each packet which has the shortest delay and transfer the packets to WONUs by means of broadcasting. Each WONU accepts its own packets and abandons the other packets.

The delay of downstream transmission in PON includes the transmission delay and the propagation delay. Assume that the OLT employs FIFO algorithm to schedule the queue. Then the transmission delay can be ignored since it is not contributing to select target WONU. The delay of downstream transmission is shown in (23) [22]. Where L_{OLT}^{i} is the length of optical fiber between OLT and $WONU_i$, $S_{optical}$ is the propagation speed of optical signals in optical fiber.

$$D_{TOTAL}^{DOWN} = L_{OLT}^{i} / S_{optical} \tag{23}$$

IV. A LOSSLESS FAULT-TOLERANCE MECHANISM COMBINING WITH PARALLEL ROUTING AND NETWORK CODING

The LFTM-PR-NC mechanism employs the network coding and parallel routing to tolerate the interruption of any one routing path which is caused by a ONU-level failure or wireless-level failure. If a routing path is interrupted, the OLT can also receive enough encoded packets to decode the packets from the other routing paths. Thus, the rapid and lossless recovery is achieved after a failure.

Supposed that the m original packets are coded to M encoded packets ($M > m$). And the M encoded packets are delivered to the destination node by means of the N parallel routing paths. The LFTM-PR-NC mechanism is composed of three stages: link statement advertisement, parallel routing calculation and network coding transmission.

A. LINK STATEMENT ADVERTISEMENT

Each node periodically broadcasts link state advertisement (LSA) to the network. Particularly, the LSAs received by WONU could be sent to OLT, since the LSAs are critical for OLT to employ an appropriate routing path for the traffic. The format of LSA is shown in Table 2.

TABLE 2. The format of LSA.

Node type	Node identification	Output links	Packet intensity	Packet loss rate	Queue length	Link capacity	Time stamp

1) *Node Type:* Wireless Router or WONU
2) *Node identification:* the uniquely identified in the network
3) *Output links:* all the links derived from the node.
    a) If the node is Wireless Router: the output links contain all the wireless links derived from the wireless router.
    b) If the node is WONU: the output links contain all the wireless links derived from the WONU and the optical link from the WONU to the OLT.
4) *Packet intensity:* the packet intensity of wireless router or WONU.
5) *Packet loss rate:* the packet loss rate (PLR) of wireless links. The optical links is considered reliable. So the PLR of optical links are set to 0.

$$E\left[T_{cycle}\right] = \begin{cases} \dfrac{KT_g}{1 - \frac{1}{\mu}\sum\limits_{i=1}^{K} \lambda_i}, & \text{if } \mathbf{HL\text{-}WONU} = \emptyset \cap \mathbf{LL\text{-}WONU} \neq \emptyset \\ \dfrac{W_{MAX}\,|\mathbf{HL}| + KT_g}{1 - \frac{1}{\mu}\sum\limits_{v_i \in \mathbf{LL\text{-}WONU}} \lambda_i}, & \text{if } \mathbf{HL\text{-}WONU} \neq \emptyset \cap \mathbf{LL\text{-}WONU} \neq \emptyset \\ K(W_{MAX} + T_g), & \text{if } \mathbf{HL\text{-}WONU} \neq \emptyset \cap \mathbf{LL - WONU} = \emptyset \end{cases} \tag{21}$$

6) *Queue length:* the queue length of the WONU. It is used to calculate the delay of optical link. If the node type is wireless router, the queue length is neglected.
7) *Link capacity:* the capacity of wireless links. It is used to calculate the delay of wireless link. If the node type is WONU, the link capacity is neglected.

TABLE 3. Example of LSA generated by wireless router.

Node type	Node identification	Output links	Packet intensity	Packet loss rate	Queue length	Link capacity	Time stamp
Wireless Router	Router A	A-B	λ_{AB}	10%	NULL	C_{AB}	T_{stamp}
		A-C	λ_{AC}	12%	NULL	C_{AC}	
		A-D	λ_{AD}	13%	NULL	C_{AD}	

TABLE 4. Example of LSA generated by WONU.

Node type	Node identification	Output links	Packet intensity	Packet loss rate	Queue length	Link capacity	Time stamp
WONU	WONU 1	WONU1-OLT	$\lambda_{\text{WONU1-OLT}}$	0	q	NULL	T_{stamp}
		WONU1-C	$\lambda_{\text{WONU1-C}}$	9%	NULL	$C_{\text{WONU1-C}}$	
		WONU1-D	$\lambda_{\text{WONU1-D}}$	10%	NULL	$C_{\text{WONU1-D}}$	

8) *Time stamp:* the time that the LSA generated. The LSAs Generated by Wireless Router and WONU are shown in Table 3 and Table 4.

B. PARALLEL ROUTING CALCULATION

Firstly, wireless router (upstream) or OLT (downstream) must calculate the number of parallel routing paths when traffic needs to be delivered. Secondly, the delay of wireless domain and optical domain are calculated and the delay of each link is considered as the weight of the links. Finally, the N shortest-delay parallel routing paths are found by reusing N times Dijkstra algorithm.

1) CALCULATE THE NUMBER OF PARALLEL ROUTING PATHS

Assume that the reliability of the traffic requirement is R, the bit error rate (BER) of a wireless link is P_e^w, and the BER of an optical link is P_e^o, Each packet has the same length and is L. Then the probability of an error-free transmission for a packet over a wireless link is shown in (24).

$$P_w = (1 - P_e^w)^L \tag{24}$$

The probability of an error-free transmission of a packet over an optical link is shown in (25).

$$P_o = (1 - P_e^o)^L \tag{25}$$

Assume that $\bar{h}_i$ is the average hops from a wireless router $R_i$to the WONUs. $\bar{h}_i$ is calculated in (26). Where $|\mathbf{W}|$ is the number of WONU in WOBAN. h_i^j is the shortest hop from the wireless router R_i to the j-th WONU.

$$\bar{h}_i = \frac{\sum_{j=1}^{|\mathbf{W}|} h_i^j}{|\mathbf{W}|} \tag{26}$$

Suppose that any one routing path contains $\bar{h}_i$ hops wireless links and one hop optical link in WOBAN. The probability that the packet was successfully transferred to the destination node using the routing path is shown in (27).

$$\bar{P}(h) = (1 - P_e^w)^{L\times\bar{h}_i}(1 - P_e^o)^L \tag{27}$$

Since the destination node can decode the encoded packets when any one routing path fails, the reliability of parallel routing paths is defined as the probability that any $N - 1$ routing path successfully transfer the packets and is shown in (28).

$$R' = C_N^1 \bar{P}(h)^{N-1}(1 - \bar{P}(h)) \tag{28}$$

Obviously, the reliability must satisfy $R' \geq R$. The number of parallel routing paths N can be calculated in (29). The minimal integer of N that satisfied (29) is considered as the number of routing paths.

$$R' = C_N^1 \bar{P}(h)^{N-1}(1 - \bar{P}(h)) \geq R \tag{29}$$

2) CALCULATE THE N WONU-DISJOINT PARALLEL ROUTING PATHS

a: ESTIMATE THE QUEUE LENGTH OF WONUs

Since the state of network is changing rapidly, the queue length of WONU in the received LSAs cannot reflect the real state of WONU. Therefore, it is significant to estimate the real state of the queue length in all the WONU. Fig. 4 shows the process from the LSA generated by WONU and the packet arrived WONU.

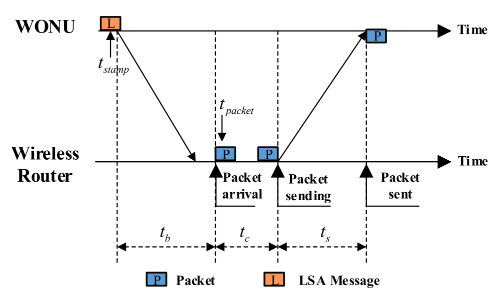

FIGURE 4. The process with LSA.

In order to reflect the real queue length of the WONU, the queue length that the packets arrived WONU could be estimated. There are three phases in the process.

- t_b is the time that from the LSA generated by the WONU to the packets arrive wireless router.
- t_c is the time between the packets arrive wireless router and the packets leave the wireless router. t_c can be neglected since it is smaller than the other part.

- t_s is the time that the packets are sent to WONU from wireless router.

t_b can be calculated by (30). Where t_{packet} is the time that the packets arrive at the wireless router and t_{stamp} is the time that the LSA is generated by the WONU.

$$t_b = t_{packet} - t_{stamp} \tag{30}$$

t_s is equal to the total back-end delay as shown in (31)

$$t_s = D_{TOTAL}^{UP} \tag{31}$$

The total time of the process is shown in (32).

$$t_{total} = t_{packet} - t_{stamp} + D_{TOTAL}^{UP} \tag{32}$$

Then the average number of packets arrived at the WONU during the total time of the process is shown in (33). Where $N(t_{total})$ is the number of packets arrived at the WONU during t_{total}, λ_i is the packet intensity of the WONU.

$$E\left[N(t_{total})\right] = \lambda_i t_{total} \tag{33}$$

The total length of the arrived packets q_{arrive} is shown in (34).

$$E\left[q_{arrive}\right] = E\left[N(t_{total})\right]/\mu = \lambda_i t_{total}/\mu \tag{34}$$

And the length of the packets sent by WONU during this process depends on the number of polling cycles included in the process. The average grant bandwidth is $E\left[W_P^{[i]}\right]$ in each polling cycle. The length of the packets sent by WONU is shown in (35).

$$E\left[q_{send}\right] = \left\lfloor \frac{t_{total}}{E\left[T_{cycle}\right]} \right\rfloor \times E\left[W_P^{[i]}\right] \tag{35}$$

Then the queue length of the WONU when the packets arrive at the WONU is shown in (36).

$$\begin{aligned} E\left[q'\right] &= q + E\left[q_{arrive}\right] - E\left[q_{send}\right] \\ &= q + \lambda_i t_{total}/\mu - \left\lfloor \frac{t_{total}}{E\left[T_{cycle}\right]} \right\rfloor \times E\left[W_P^{[i]}\right] \end{aligned} \tag{36}$$

Therefore, the queue length q in LSA can be replaced by $E\left[q'\right]$. The delay of upstream transmission which is calculated by $E\left[q'\right]$ can reflect the real state of the network.

In the downstream transmission, the queue length of WONU should not be updated since the OLT can easily obtain the queue length of WONU according to DBA.

b: LINK WEIGHT ASSIGNMENT

According to parameters in the received LSAs, the delay of wireless links and optical links are calculated by wireless router (upstream) or OLT (downstream) and the delay of each link is set as the weight of the links.

Algorithm 1

Input: the network graph G and the weight of each link
Output: the N WONU-disjoint parallel routing paths

```
Initialize the graph G, the weight of each link
let the auxiliary graph G' = G and i = 1
while i ≤ N do
    find the shortest delay path according to
    Dijkstra algorithm in G'. And the path is
    denoted as P_i
    delete all the links of P_i in G' including wireless
    and optical links
    i = i + 1
end while
the set of paths P = {P_1, P_2, ··· , P_N} is the N
WONU-disjoint parallel routing paths
```

c: PARALLEL ROUTING COMPUTATION

In order to avoid the interaction effect between N routing paths when a ONU-level failure occurs, the WONU-disjoint parallel routing paths are employed in LFTM-PR-NC mechanism. As shown in algorithm 1, the Dijkstra algorithm is applied for N times to search for the N WONU-disjoint parallel routing paths.

C. NETWORK CODING TRANSMISSION

In the upstream transmission, the m original packets are coded to the optimal number of encoded packets by the wireless router to minimize the cost of recovery. And the M encoded packets are sent to OLT by the N WONU-disjoint parallel routings in accordance with the packets allocation scheme to tolerate any failures with the minimum number of encoded packets. The m original packets can be obtained when the OLT receive m linearly independent encoded packets and decode the encoded packets. In the downstream transmission, vice versa.

1) PACKETS ALLOCATION SCHEME

The packets allocation problem is how to assign M encoded packets to the N WONU-disjoint parallel routings. The number of encoded packets transmitted on each path is different, so the number of lost packets is also unequal.

As shown in Fig. 5, the 8 original packets are coded to 12 encoded packets. Then the 12 encoded packets in the wireless router are needed deliver to the OLT and there are three parallel routing paths for transferring the 12 encoded packets. The encoded packets can be decoded when the OLT receive 8 encoded packets. In Fig. 4 (a), the encoded packets are allocated with (5, 2, 5) for the three parallel paths. When the link between WONU1 and OLT is failed, the OLT can only receive 7 encoded packets and cannot decoded these encoded packets. Since the OLT does not receive enough encoded packets for decoding. In Fig. 4 (b), the encoded packets are allocated with (4, 4, 4). The OLT can receive 8 encoded packets when any one link fails. It is enough to decode the

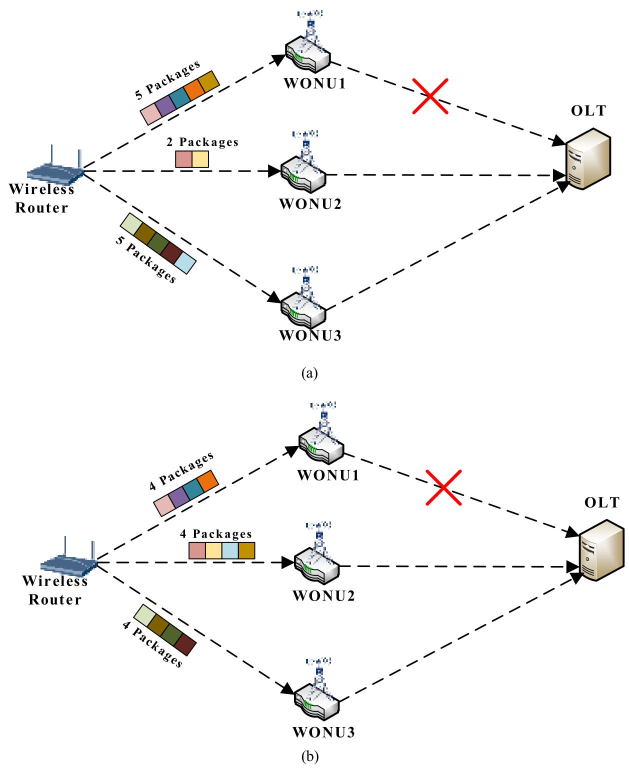

FIGURE 5. **The example of packets allocation. (a) Example 1: packets allocation with (5, 2, 5). (b) Example 2: packets allocation with (4, 4, 4)**

encoded packets. Therefore, the packets allocation scheme is significant for LFTM-PR-NC mechanism to tolerate any failures.

In the case of fixing the number of encoded packets M, whether the OLT can receive m linearly independent encoded packets is determined by the packets allocation scheme. Obviously, different packets allocation schemes require different number of encoded packets M to recover the original packets when any one path fails. Because the number of lost packets are different when different path fails.

The objective of LFTM-PR-NC mechanism is to find the optimal packets allocation scheme that need minimum number of encoded packets M to recover the original packets when any one routing path interrupts.

Assume that all the encoded packets are linearly independent. n_k represents the kth parallel routing, x_k is the number of encoded packets transmitted on n_k. We consider that if a routing path interrupts which is caused by a ONU-level failure or wireless-level failure, the whole encoded packets transmitted on this path are lost. The OLT cannot receive these lost packets.

Then we can get (37).

$$x_1 + x_2 + \cdots + x_k + \cdots + x_N = M, \quad 1 \le k \le N \tag{37}$$

Assume that x_k is sorted in ascending order as shown in (38).

$$0 < x_1 \le x_2 \le \cdots \le x_k \le \cdots \le x_N < M, \quad 1 \le k \le N \tag{38}$$

Lemma 1: Without considering the packets loss on wireless links and optical links, when any one of the N parallel routing paths fails, the necessary and sufficient condition that the m original packets can be recovered by the OLT is that the total number of encoded packets which are received from the other $N-1$ parallel routing paths by OLT must more than or equal to m.

Proof: Sufficiency. When any one of the N parallel routing paths fails, the OLT can only receive packets from the other $N-1$ parallel routing paths. When the OLT receive at least m encoded packets from the other $N-1$ parallel routing paths, the m original packets can be recovered according to network coding.

Necessity. If the OLT can recover the m original packets when any one of the N parallel routing paths fails, obviously, the OLT must receive at least m encoded packets from the other $N-1$ parallel.

Proved end.

Lemma 2: If the source node delivers the M encoded packets to destination node through N parallel routing paths, then the maximum number of encoded packets transmitted on a single path should satisfy $x_{\max} \ge M/N$, the minimum number of encoded packets transmitted on a single path should satisfy $x_{\min} \le M/N$.

Proof: Equation (39) can be obtained according to (37) and (38)

$$x_1 + x_2 + \cdots + x_k + \cdots + x_N = M \le N \cdot x_N \tag{39}$$

The minimum number of x_N is shown in (40).

$$x_{\max} = x_N \ge M/N \tag{40}$$

Similarly, we can get (41) according to (37) and (38).

$$x_1 + x_2 + \cdots + x_k + \cdots + x_N = M \ge N \cdot x_1 \tag{41}$$

Then the maximum number of x_1 is shown in (42).

$$x_{\min} = x_1 \le M/N \tag{42}$$

Proved end.

Theorem 1: Without considering the packets loss on wireless links and optical links, when any one of the N parallel routing paths fails, based on the condition that the OLT can recover m original packets, the optimal packets allocation scheme, which result in the minimum number of encoded packets for decoding, is shown in (43).

$$x_1 = x_2 = \cdots = x_k = \cdots = x_N = M/N, \quad 1 \le k \le N \tag{43}$$

Proof: According to lemma 1, the m original packets can be recovered by OLT only if the OLT receive at least m encoded packets when any one of the N parallel routing paths fails. Assume that parallel routing n_N fails. Then the OLT must receive m encoded packets from the other $N-1$ paths to decoding the encoded packets as shown in (44).

$$x_1 + x_2 + \cdots + x_k + \cdots + x_{N-1} \ge m \tag{44}$$

In order to minimize the total number of encoded packets M, the number of packets transmitted on the other $N-1$ paths should be the minimum value m as shown in (45).

$$x_1 + x_2 + \cdots + x_k + \cdots + x_{N-1} = m \tag{45}$$

According to (37) and (45), we can obtain (46).

$$x_1 + x_2 + \cdots + x_k + \cdots + x_{N-1} = m = M - x_N \tag{46}$$

Then

$$M = m + x_N \tag{47}$$

According to lemma 2 and (47), the minimum number of M is shown in (48).

$$M = m + x_N \geq m + M/N \tag{48}$$

Therefore, the total number of encoded packets M can be the minimum value only if $x_N = M/N$. And the minimum value of M is $m + M/N$.

When parallel routing n_{N-1} fails, the number of encoded packets transmitted on the other $N-1$ paths must be m in order to minimize the total number of encoded packets M as shown in (49).

$$x_1 + x_2 + \cdots + x_k + \cdots + x_{N-2} + x_N = m = M - x_{N-1} \tag{49}$$

And then

$$M = m + x_{N-1} = m + M/N \tag{50}$$

Therefore, the total number of encoded packets M can be the minimum value only if $x_{N-1} = M/N$.

Similarly, the total number of encoded packets M can be the minimum value only if $x_1 = x_2 = \cdots = x_N = M/N$.

Proved end.

According to theorem 1, the optimal packets allocation scheme is that the number of packets transmitted on all parallel routing paths are equal to M/N which could need a minimum number of encoded packets for recovering m original packets when any one of the N parallel routing paths fails.

2) OPTIMAL NUMBER OF ENCODED PACKETS

The number of encoded packets could affect the network load. Since the more number of encoded packets, the larger the network load, the minimum number of encoded packets which is the optimal number of encoded packets could result in the minimum cost of recovery.

Assume that $\mathbf{P} = \{\mathbf{P}_1, \mathbf{P}_2, \cdots, \mathbf{P}_i, \cdots, \mathbf{P}_N\}$ is the set of N parallel routing paths and $\mathbf{P}_i = \{e_1, e_2, \cdots\}$ is the set of links in the ith routing path.

Theorem 2: Without considering packet loss in wireless links and optical links, based on the condition that the OLT recover m original packets when any one of the N parallel routing paths fails. Then the minimum number of encoded packets M is $\frac{N}{N-1}m$ and the encoded packets transmitted on each path is equal to $\frac{m}{N-1}$.

Proof: According to theorem 1, the number of packets transmitted on all parallel routing paths are equal to M/N when the number of encoded packets are minimized. The number of encoded packets transmitted on any $N-1$ paths must be more than or equal to m to decode the encoded packets when any one of the N parallel routing paths fails. Then (51) can be obtained.

$$x_1 + x_2 + \cdots + x_{N-2} + x_{N-1} = (N-1)\frac{M}{N} \geq m \tag{51}$$

Then the minimum number of encoded packets is shown in (52).

$$M \geq \frac{N}{N-1}m \tag{52}$$

Thus, the minimum number of encoded packets M is equal to $\frac{N}{N-1}m$. And the number of encoded packets transmitted on each path is shown in (53).

$$x_1 = x_2 = \cdots = x_N = \frac{M}{N} = \frac{m}{N-1} \tag{53}$$

Proved end.

According to theorem 2, the minimum number of encoded packets is obtained without considering packet loss in wireless links and optical links. However, due to the instability of the wireless links, each wireless link could lose packets. The OLT could receive less than m encoded packets from any $N-1$ routing paths which may result in decoding failure. Thus, the number of encoded packets M must increase in accordance with the packet loss rate on each routing path so that the OLT can receive enough encoding packets and reduce retransmission.

The OLT should receive at least $m/N-1$ encoded packets from each routing path to guarantee receiving enough encoded packets for decoding if some packets are lost in wireless links.

Assume that E_j is the packets loss rate of the jth link in $\mathbf{P}_i = \{e_1, e_2, \cdots\}$. Then the probability that a packet successfully transmits from wireless router to OLT by $\mathbf{P}_i$ is shown in (54).

$$P_{packt} = \prod_{e_j \in \mathbf{P}_i} (1 - E_j) \tag{54}$$

Assume that x_i' is the number of encoded packets transmitted on the ith path after considering the packet loss rate.

Then the number of packets that successfully arrived the OLT must more than $m/N-1$ as shown in (55).

$$x_i' \times P_{packt} = x_i' \times \prod_{e_j \in \mathbf{P}_i} (1 - E_j) \geq m/N - 1 \tag{55}$$

Then the number of packets transmitted on each path is shown in (56). For reducing network load, the minimum of x_i' is employed.

$$x_i' \geq \frac{m}{(N-1) \times \prod_{e_j \in \mathbf{P}_i} (1 - E_j)} \tag{56}$$

Therefore, the optimal number of encoded packets M is updated in (57).

$$M = \sum_{i=1}^{N} x_i' = \sum_{i=1}^{N} \frac{m}{(N-1) \times \prod\limits_{e_j \in \mathbf{P}_i} (1 - E_j)} \tag{57}$$

Then the updated number of encoded packets M contains three parts as shown in (58).

$$M = m + R_1 + R_2 \tag{58}$$

The first part is the number of original packets m. R_1 is the redundant number of encoded packets which is used to tolerate any one path fails that caused by an ONU-level or wireless-level failure. R_1 can be calculated in (59).

$$R_1 = \frac{N}{N-1} m - m = \frac{m}{N-1} \tag{59}$$

R_2 is the redundant number of encoded packets which is used to tolerate the losing of packets in the destination node. Thus, the original packets can not be recovered by the destination node. R_2 can be calculated in (60). This part of redundant packets is necessary for any routing mechanism. Since the losing of packets exists at all the networks. If this part of redundant packets is not employed, the lost packets must be retransmitted. However, the retransmission of lost packets could result in a long delay. Furthermore, the destination node must record the serial number of all the packets and identify which packets are lost if the network coding is not employed.

$$R_2 = \sum_{i=1}^{N} \frac{m}{(N-1) \times \prod\limits_{e_j \in \mathbf{P}_i} (1 - E_j)} - \frac{N}{N-1} m \tag{60}$$

Therefore, the total redundant number of encoded packets R_{Total} could be the sum of R_1 and R_2 as shown in (61). Although so much redundant encoded packets are employed in our mechanism, the network does not experience serious congestion. Since the parallel routing is very useful to reduce network congestion and achieve load balancing [28].

$$R_{Total} = R_1 + R_2 = \sum_{i=1}^{N} \frac{m}{(N-1) \times \prod\limits_{e_j \in \mathbf{P}_i} (1 - E_j)} - m \tag{61}$$

3) CODING PACKETS AND TRANSMISSION

Assume that $X_1, X_2, \cdots, X_m$ represent the m original packets, $Y_1, Y_2, \cdots, Y_M$ represent the M encoded packets. $a_i = (\xi_1, \xi_2, \cdots\cdots, \xi_m)$ represent an encoding vector which is randomly selected from Galois field. The M group coding vector is selected to encode M packets. The coding method is shown in (62) [29].

$$Y_i = \sum_{j=1}^{m} \xi_j X_j \tag{62}$$

The M encoded packets are sent to the OLT by means of the N parallel routing paths. When the OLT receives m linearly independent encoded packets, the m original packets can be recovered in the destination node.

The Pseudo-code of LFTM-PR-NC mechanism is shown in Algorithm 2.

Algorithm 2 LFTM-PR-NC Algorithm

```
• Link Statement Advertisement
  For each node u advertise periodically the LSA to
  wireless nodes including WONUs and wireless
  routers
  if node u is a WONU, then
    Send all the delay of wireless link to the OLT
      Advertise the LSA to the wireless nodes including
      wireless routers and the other WONU
  else if node u is a wireless router, then
      Advertise the LSA to the wireless nodes including
      wireless routers and WONUs
  end if
• Parallel Routing Calculation
  calculate the number of paths N which satisfied the
  reliability R
    if the traffic is upstream, then
        calculate the polling cycle E[T_cycle] and grant
        bandwidth E[W_P^[i]]
        estimate the queue length of WONUs q'
        according to q, E[T_cycle] and E[W_P^[i]]
        calculate front-end delay and back-end delay
    else if the traffic is downstream, then
        calculate front-end delay and back-end delay
    end if
  assign link weight for all the wireless and optical
  links
  find the N WONU-disjoint parallel routing paths
  using Algorithm 1
• Network Coding Transmission
  if the node u is a source node, then
      calculate the optimal number of encoding packets
      and the number of packets transmitted on each
      path
      encode the m original packets to M encoding
      packets by network coding
      send the encoding packets to the N parallel
      routing paths according to the packets allocation
      scheme
  else if node u is destination node, then
      if node u received m linear independence
      encoding packets, then
          decode the encoded packets and recover m
          original packets
      end if
  end if
```

V. NUMERICAL RESULTS

The NS2 [30] is employed to simulate the LFTM-PR-NC mechanism. There are 25 wireless routers employed in WOBAN and 5 WONUs are deployed on the edge. The traffic is generated with Poisson distribution. Each wireless router is equipped with one radio with a capacity of 54 *Mbps*. The upstream and downstream data rate of PON is 1 *Gbps*. The distance between WONU and OLT is set to 10 *Km* which could result in a 50 *us* propagation delay on the optical links.

We compare the performance of LFTM-PR-NC mechanism with the RADAR [21] which achieves minimum delay and self-healing in case of network failures.

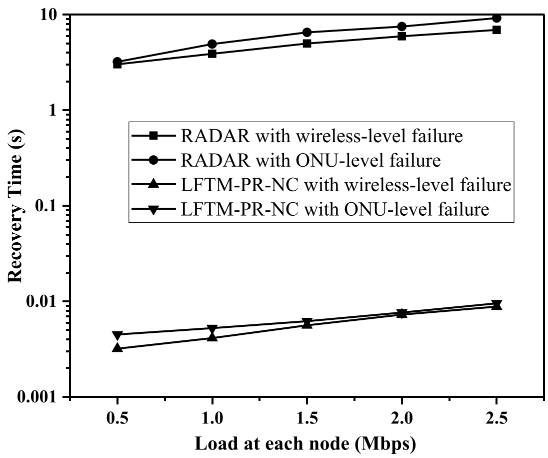

FIGURE 6. The recovery time with different failure.

The result of recovery time is shown in Fig. 6. The recovery time of LFTM-PR-NC mechanism is less than 10 *ms*. Obviously, it is significantly cut down compared to RADAR. It is due to the fact that the recovery time of RADAR includes the time of detecting failure, the time of finding an alternate path for the interrupted traffic and the path switching time. These three stages could result in a long recover time and a large number of packets lost. However, the LFTM-PR-NC mechanism does not need to detect the failure and find another path when a routing path fails. The destination node can recover the original packets by means of receiving enough encoded packets from the other $N - 1$ paths when any one of the parallel routing paths is failed. As a result, the recovery time of LFTM-PR-NC mechanism is equal to transmission time of encoded packets over the parallel routing paths. It is worth noting that the loss of encoded packets does not result in the loss of original packets since the redundant encoded packets are employed in the mechanism.

The average delay of LFTM-PR-NC mechanism and RADAR is shown in Fig. 7. The average delay of LFTM-PR-NC mechanism is 44% less than RADAR on average. It is due to the fact that the N parallel routing paths are employed in LFTM-PR-NC mechanism to deliver the traffic. The parallel routing takes full advantage of the idle bandwidth to transmit the packets which could significantly cut down the delay. Meanwhile, the shortest delay paths are employed

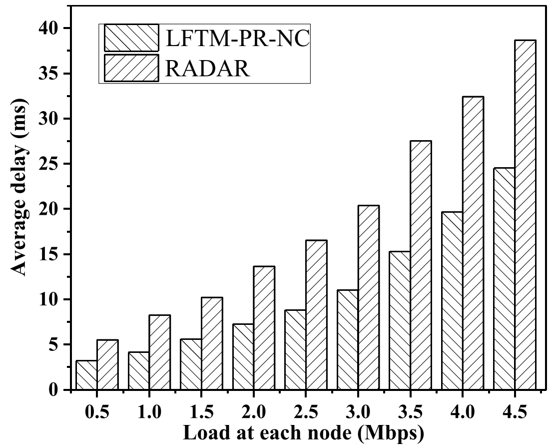

FIGURE 7. The average delay with LFTM-PR-NC and RADAR.

when searching for the N parallel routing paths. Furthermore, in LFTM-PR-NC mechanism, the lost packets which are caused by the failure and the instability of wireless links do not need to be retransmitted because the redundant encoded packets are considered for the lost packets in the coding process. However, all the lost packets must be retransmitted in RADAR.

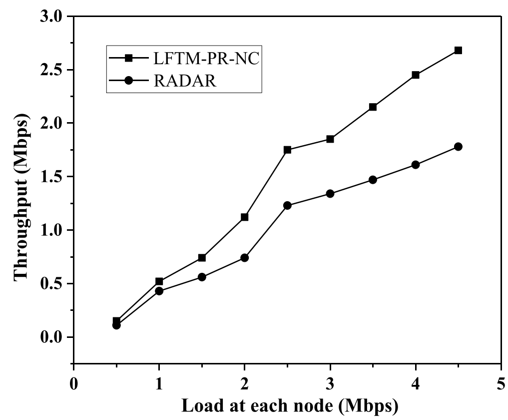

FIGURE 8. The throughput with LFTM-PR-NC and RADAR.

The throughput with LFTM-PR-NC mechanism and RADAR is shown in Fig. 8. It is because that the LFTM-PR-NC mechanism employed parallel routing which can significantly promote the throughput by exploiting the spare resources of WOBAN. The throughput could be restricted by the load unbalancing which results in a heavy packet loss. The parallel routing can achieve load balancing and fully utilize available bandwidth. Furthermore, the network coding method also help the throughput.

The redundancy rate (RR) for R_1 is defined as the ratio of R_1 and m. Since this part of redundant packets is used to ensure that the destination node can receive m encoded packets. The results of RR for R_1 are shown in Fig. 9. Obviously, as the number of paths increases, the RR gradually decreases. This is because that the number of lost packets which are

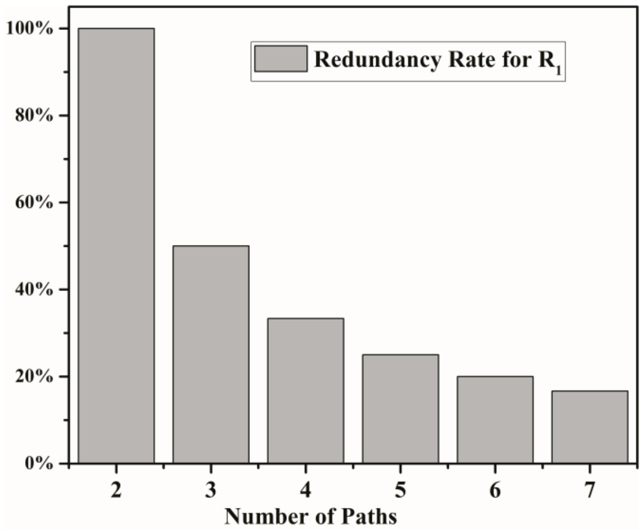

FIGURE 9. The redundancy rate for R_1.

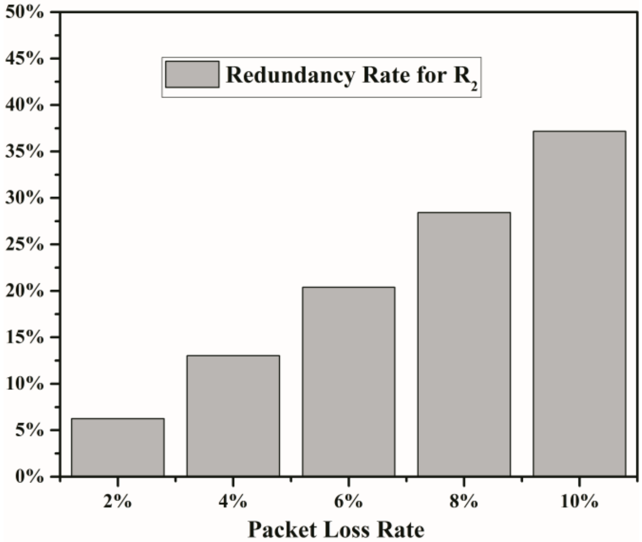

FIGURE 10. The redundancy rate for R_2.

caused by the failure of any one path are decreased when the number of paths increase.

The redundancy rate (RR) for R_2 is defined as the ratio of R_2 and $\frac{N}{N-1}m$. since this part of redundant packets is used to ensure that the destination node can receive $\frac{N}{N-1}m$ encoded packets. The results of RR for R_2 are shown in Fig. 10. As the packet loss rate increases, RR gradually increases. Since the original node must send more encoded packets to ensure that the destination node can receive enough encoded packets to recover original packets when the packet loss rate increases.

The redundancy rate (RR) for R_{Total} is defined as the ratio of R_{Total} and m. The results of RR for R_{Total} are shown in Fig. 11. Obviously, as the number of paths decreases and the packet loss rate increases, the total number of redundant encoded packets increases rapidly. However, due to

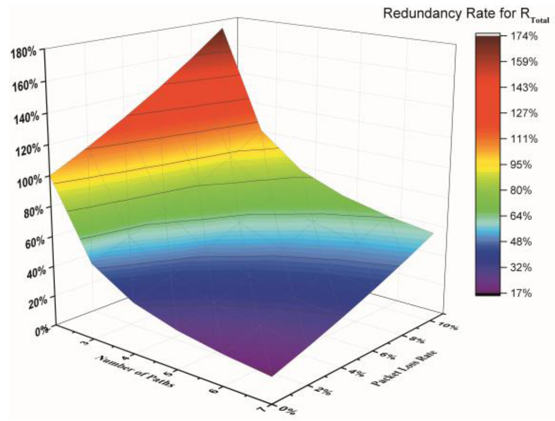

FIGURE 11. The redundancy rate for R_{Total}.

the employment of parallel routing, the WOBAN could not encounter heavy congestion. Since parallel routing have the advantages of reducing the congestion, it is useful to deal with the negative effect of LFTM-PR-NC mechanism.

VI. CONCLUSION

In this paper, we have proposed a lossless fault-tolerance mechanism combining with parallel routing and network coding (LFTM-PR-NC) mechanism to enhance the survivability of WOBAN against any ONU-level failure and wireless-level failure. The LFTM-PR-NC mechanism provides the capacity of tolerating any one failure of the routing paths by means of combining parallel routing and network coding. The destination node can recover all the original packets by receiving enough encoded packets from the other routing paths if any one path failed. Simulation results show that the LFTM-PR-NC mechanism can significantly improve the recovery time without any redundant backup fiber. Furthermore, the network performance is also improved at the same time.

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