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Fundamental Analysis of Nonlinear Bypass Route Computation for Wired and Wireless Network Cooperation Recovery System

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Abstract—A wired and wireless network cooperation (NeCo) system was proposed to quickly recover civilian telecommunication services in the aftermath of a catastrophic disaster. The NeCo system achieves both rapid recovery and high throughput using wireless bypass routes backhauled by wired networks. However, the routing method did not consider throughput reduction caused by sharing of wireless resources among dead nodes. This paper evaluates resultant throughout performance of NeCo system that employs a nonlinear bypass route computation considering the wireless resource sharing.

1. Introduction

The world is often stricken by catastrophic disasters such as earthquakes, hurricanes, and tsunamis. When such disasters strike, disaster-response operations are critical to the prevention of death and injury. During such operations, telecommunication systems are essential to both emergency responders. However, it is also often disrupted in disaster period. Life-saving operations become exceedingly challenging when emergency responders and civilians are left without any means of communication.

For emergency network management and business continuity during disasters, a network-recovery program has been developed [1]. Many works have focused on how to facilitate communications among emergency responders using wireless mesh networks [2, 3]. For both emergency responders and civilians, a solution that employs a wireless multi-hop backhauled network together with self-organization capabilities powered by renewable energy was proposed [4]. Solar power is one candidate for powering such wireless networks after disasters [5]. Typical network-access services for civilians are constructed with wired networks of optical fibers, including PONs. Although the rapid recovery of optical networks can be achieved with redundant systems [6], such systems cannot deal with the wide range of failures resulting from disasters. For wide-area communication recovery, a wireless bypassing system for PONs was proposed [7].

To achieve quick recovery and high wireless link throughput, the NeCo system was proposed [8]. With NeCo, dead leaf nodes in disrupted wired networks immediately recover communication through wireless bypass routes to surviving nodes. The optimal bypass routes are computed to maximize the expected throughput by solving a linear programming problem. It can achieve both rapid communication recovery and high throughput.

Meanwhile, the previously proposed routing method did not consider throughput reduction caused by sharing of wireless resources among dead nodes [9]. This paper proposes a bypass route computation method considering the wireless resource sharing.

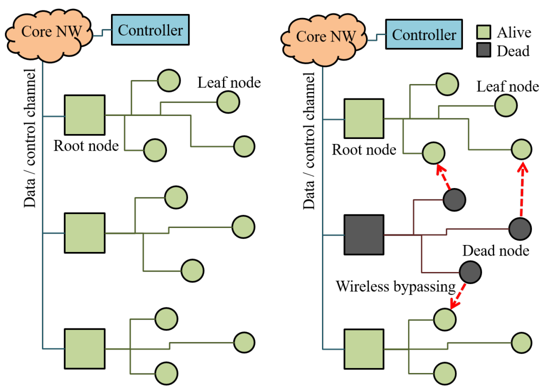
The rest of the paper is organized as follows. Sect. 2 describes the system model with brief summary of previous proposal. Sect. 3 presents the newly proposed nonlinear routing method. Sect. 4 shows computer simulation results and Sect. 5 then concludes this paper.

2. NeCo system

2.1. Overview

The concept of the NeCo system is shown in Fig. 1. The network consists of root nodes and leaf nodes. The root nodes are assumed to be placed in central offices, and connected to core networks. The leaf nodes are connected to the root nodes via wired networks such as optical fibers. A controller is installed to establish a logical connection to each leaf node.

The recovery sequence is shown in Fig. 2. In normal periods, the leaf nodes communicate with the root nodes using the wired networks. When a traffic disruption is detected, the state of the leaf node is changed to dead and wireless communication function is activated. The alive nodes report the reception power for the dead nodes. The controller calculates optimal bypass routes to maximize the throughput of the wireless bypass routes. Then, the alive nodes establish wireless links to designated dead nodes. As a consequence, dead nodes can recover communication using the bypass routes.



(a) Normal period (b) After disaster

Figure 1: Concept of the NeCo system.

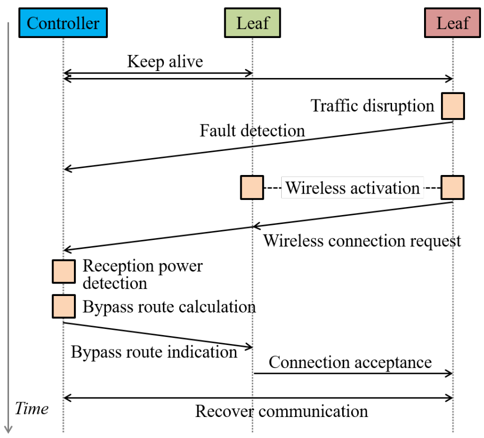


Figure 2: Recovery sequence for the NeCo system.

2.2. Routing

The bypass routes between dead and alive nodes were calculated with the linear programming problem. The objective function is maximizing the expected wireless throughput. Let i, j denote the identifiers for the leaf nodes. The state of j-th node is represented by a binary parameter y_j; $y_j = 1$ is alive, and $y_j = 0$ is dead. The achievable physical layer wireless transmission rate between the i-th and j-th nodes is represented as $d_{i,j}$, which is decided by the reception power $p_{i,j}$. We define $d_{i,i} = 1(i = j)$. Let A_j denote the maximum number of dead nodes linked to the j-th node. It should be pointed that the achievable bandwidth decreases in accordance with the number of dead nodes connected to the same alive node because the wireless bandwidth is shared among them. $x_{i,j}$ denotes the state of the bypass route between the i-th and j-th nodes; $x_{i,j} = 1$ represents that i-th dead node is connected to j-th node, and $x_{i,j} = 0$ otherwise. Based on the definitions above, the linear programming problem is formulated as:

$$\text{Max} \sum_i \sum_j x_{i,j} d_{i,j} \tag{1}$$

s.t.

$$y_j = x_{j,j} \quad \forall j \tag{2}$$

$$y_j d_{i,j} - x_{i,j} \geq 0 \quad \forall i, j \tag{3}$$

$$\sum_j x_{i,j} \leq 1 \quad \forall i \tag{4}$$

$$\sum_i x_{i,j} \leq A_j + 1 \quad \forall j \tag{5}$$

$$x_{i,j} = 0, 1$$

The objective function is the total expected throughput of bypass routes (1). It is defined that $x_{j,j} = 1$ is satisfied for $y_j = 1$ (2). i-th dead node can be connected to j-th node that satisfies $y_j = 1$ and $d_{i,j} = 1$ (3). The maximum number of bypass route for a single node is one (4). As stated before, the maximum number of dead nodes connected to a single alive node is A_j (5).

With this formulation, the expected total wireless link rate is maximized based on the signal reception power between leaf nodes. This linear programming problem is easy to solve, however, it does not consider the division loss in throughput due to the shared wireless bandwidth among multiple dead nodes connected to the same alive node. When multiple dead nodes are linked to the same alive node, the achievable throughput is reduced more than the expected value calculated in the formulation above. This throughput degradation would become unnegligible if A_j is set to a large value.

3. Proposed routing

3.1. Concept

This paper modifies the formulation described in Sect. 2.2 to a nonlinear programming problem considering the shared wireless bandwidth. With the proposed routing method, better bypass routes with higher throughput can be found even if overlapped routes increase with the previous method.

3.2. Formulation

The objective function is total expected throughput observed in alive nodes. It is defined as the physical layer wireless transmission rate determined by the reception power and the bandwidth sharing.

$$\text{Max} \sum_i \sum_j \frac{x_{i,j} d_{i,j}}{\sum_i x_{i,j}} \tag{6}$$

The constraints are same as the existing method in (2)-(5).

3.3. Algorithm

To solve the nonlinear problem, in this paper we employ a Monte Carlo based approach. First, the initial bypass

Table 1: Simulation parameters

Item	Value
Carrier frequency	4.9 GHz
System bandwidth	40 MHz
Wireless interface	IEEE802.11ac [10]
RTS/CTS	Off
Number of antenna	1, Omni-directional
Number of channel	1
Guard interval length	Short: 400 nsec
Transmission power	23 dBm
Antenna gain	13 dBi
Channel model	Free space propagation
Traffic model	Poisson origination, Log-normal distribution UDP Packet: 1500 bytes, Average: DL: 20, UL: 3 [12] Load ratio DL:UL = 6:1 [13]

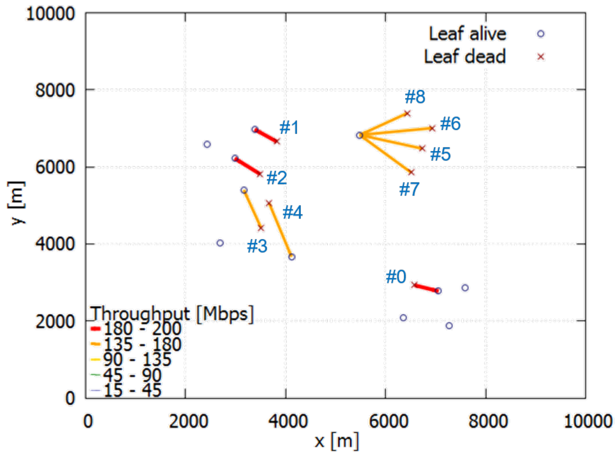
routes are chosen by random selection considering the constraints. In the random process, the occurrence probabilities of each route are proportionally distributed as their reception powers. With this approach, the routes with larger reception power are more likely to be selected. Based on the selected routes, the objective function is calculated. Then, the bypass routes are randomly selected again. After the certain times of iteration, the best routes that maximizes the objective function are selected.

4. Computer simulation

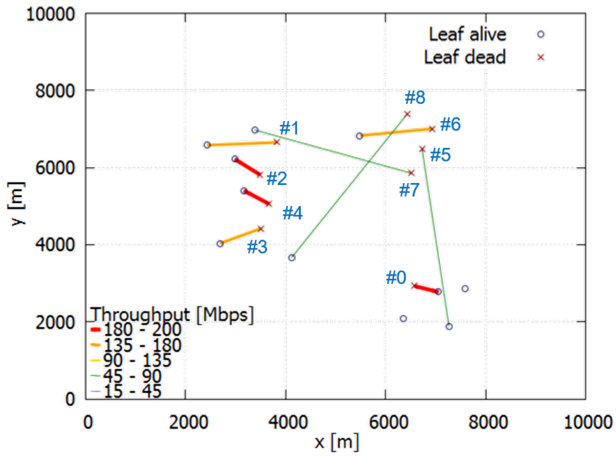
4.1. Simulation Condition

There were 20 leaf nodes in an 10-square kilometer area. Their positions were randomly determined, and the state of each node was randomly set as alive or dead. Upper limit of wireless connection A_j is set to 4.

Simulation parameters are listed in Table 1. Wireless nodes are based on the IEEE802.11ac interface [10] which can be mounted at low cost. Employing 4.9 GHz band for outdoor use [11], each node is assumed to have a single omni-directional antenna with 13 dBi gain for transmission and reception. The achievable wireless link throughput depends on reception power and is determined based on these parameters [9]. Since wireless nodes are installed at top of building, we can expect line-of-sight (LoS) channel environment. Free space propagation model is assumed in the evaluation. Since all nodes are in carrier sense range, request-to-send (RTS) and clear-to-send (CTS) handshakes are not used. The Poisson origination is employed as a traffic model. The number of data packets per session is randomly determined by the log-normal distribution, the mean of which is 20 for downlink and 3 for uplink [12]. The ratio of the total offered load of downlink to uplink is 6 : 1 [13].



(a) Previous method



(b) Proposed method

Figure 3: Simulated topology and routing results.

User Datagram Protocol (UDP) traffic is also assumed and we focused on MAC level performance. System throughput Γ is defined as aggregated MAC level throughput for all packet transmissions each of which successfully delivered to a destination; $\Gamma = (1500 \times 8)N_{rx}/T_{sim}$ [bps] where N_{rx}, and T_{sim} stand for the total number of received packet and simulation period, respectively. Here assumes 1500 bytes of data packet size. Each simulation is carried out for T_{sim} = 120 seconds which ensures a good convergence.

4.2. Simulation Results

Resultant topology and routing is shown in Fig. 3. Evaluation focuses on the 5-8th dead nodes which are connected to the same alive node with the previous method [8]. The proposed method successfully avoid selecting overlapped alive node. Fig. 4 shows corresponding downlink MAC level throughout for each node. The 6th dead node can enjoy improved throughput since bandwidth division has been avoided. Meanwhile, the other nodes are forced to connect to distant alive nodes and exhibit reduced through-

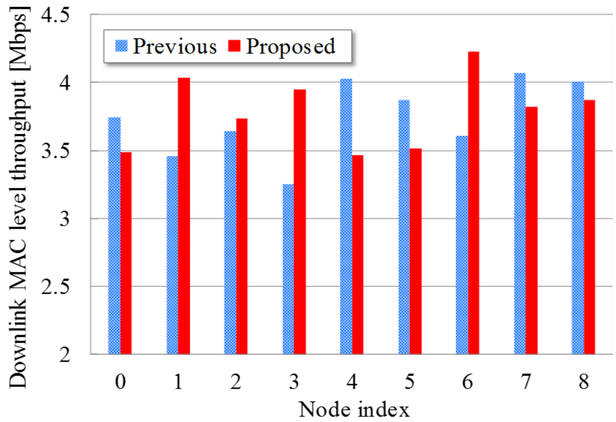


Figure 4: Downlink MAC level throughput for each node.

put value; system throughput is reduced by 14%. This performance reduction can be compensated if available alive nodes exist near these dead nodes. Depending on the network topology, the previous method sometimes causes reduced throughput due to the bandwidth sharing. The proposed nonlinear routing can be expected to resolve such unfair situation while keeping improved system throughput compared to the conventional one.

5. Conclusion

This paper proposed a nonlinear bypass route computation method considering the wireless resource sharing among dead nodes for the NeCo system, which achieves both rapid recovery and high throughput using wireless bypass routes backhauled by wired networks. Computer simulation confirmed that the proposed routing method can avoid bandwidth division loss although it cannot always improve the total throughput performance. Detailed performance should be further investigated through simulations with large-scale network topologies.

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