A Self-adaptive Reconfiguration Scheme for Throughput Maximization in Municipal WMNs

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Abstract

Multi-hop wireless mesh network (WMN) is considered to be an economical technique for last-mile broadband Internet access [1]. Fueled by the rapid development of the Internet of Things, it is increasingly important to provide robust and high-quality urban wireless mesh networks (WMNs) for public service. However, WMNs encounter frequent link failures during their lifetime in practical use as a consequence of large-scale wireless interference, block buildings, etc., which deeply influences the performance of the network. These failures should be recovered in time or prevented with foresight. Tremendous labor and management cost should also be avoided. In this paper, we focus on an interesting phenomenon called “loop effect” in urban WMNs which may cause frequent link failures. A scheme named *anti-loop network reconfiguration system (ALRS)* for link recovery in municipal WMNs with QoS requirement is proposed and analyzed. ALRS takes the historical information into consideration to achieve maximum throughput, interference avoidance and self-reconfiguration with no requirement on mesh node antennas. Our evaluation results show that ALRS outperforms all the existing techniques in improving network throughput and reducing the occurrence probability of continuous link failure.

Keywords: reconfiguration; throughput; municipal WMN; optimal

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1. INTRODUCTION

Wireless mesh networks (WMNs) are being used and deployed widely all around the world for various reasons such as public safety, environmental monitoring and city-wide wireless Internet services [3, 4]. Although faced with some difficulties, WMN is thought to be a preferred municipal Internet service provider [5] with huge potential due to its automatic connection, ease of installation, dynamic route discovery, flexibility and other advantages. Meanwhile, people benefit from the transformations of WMNs(e.g., using multi-radio/multi-channel systems [6, 7, 8]) in utilizing it with different purposes, among which, municipal network with higher quality of service (QoS) is the most common application scenario, and municipal WMNs experience increasing interest and attention in providing quality-guaranteed cost-efficient services. For example, Singapore and the city of Cambridge intend to construct city-wide ubiquitous Internet access with WMNs[9], and China is also planning to provide municipal WMNs in plenty of cities. The research on providing QoS-guaranteed municipal WMNs is in urgent need.

Because of the natural defects of the wireless transmission, deploying municipal WMNs is faced with challenges such as guaranteeing robustness and avoiding interference. Meanwhile, constraints like high throughput, robustness, interference avoidance and financial restriction must be considered simultaneously as well when we are trying to provide city-wide Internet access. In this case, a multi-channel multi-radio scheme (mr-WMN) mentioned in several studies [1, 9, 10, 11, 12] is considered to be a suitable choice to meet all the requirements above-mentioned. Instead of a single antenna, the mesh node (or router, AP) is equipped with two or even more antennas to achieve simultaneous message exchanging among several adjacent mesh nodes by selecting orthogonal channels appropriately. mr-WMN scheme is good at achieving high throughput with flexibility and expandability of the network maintained. But on the other hand, it is also criticized for its high link failure frequency. This is due to the natural risk of link failure and interference in wireless transmission and mr-WMN indeed aggravates it. There are some works[11, 12] concentrating on making a quick and automatic recovery from link failures caused by “ripple effect” in mr-WMNs, but

their works do not pay attention to another serious problem that is mainly occurred in urban area — the “loop effect”.

The “loop effect” is also a phenomenon in describing the occurrence of frequent link failures — but occurs in urban areas and is mainly caused by the regularity of city activities. In the city, people are more likely to be gathered due to some periodical reasons, such as at the main streets during the rush hour, at a museum at the weekend, etc. These phenomena generate a huge burden as well as interference area to wireless transmission because people are mostly carrying their cellphones. On the other hand, unexpected blocks such as newly constructed buildings may influence the wireless transmission as well, which may lead to unpredictable or long-time link failures. These influences are human related and common in urban area. We propose and define the “loop effect” as the frequent link failures caused by human activities in the urban area. According to our knowledge, it is the first time to consider the influence of human characters to the performance of WMNs.

Numerous works have been proposed to deal with the interference issue in mr-WMNs, among which, recovery from link failures [13, 14] is most widely studied with plenty of solutions presented. There are three important rules to follow both in link recovery and pursuing robustness:

- 1 **Persistence Requirement:** The network should not stop serving after deployed. If recovery needs manual operation, the interruption of network service is inevitable
- 2 **Financial Constraint:** Without self-reconfiguration mechanism, non-ignorable time and labor cost are unavoidable during the recovery of the network and cost extra expenses.
- 3 **Fluency Requirement:** The network may not experience frequent indisposed service, due to which the frequency of link failures should be limited.

The latest works [11, 12] on link recovery in mr-WMNs have already met the first two conditions. They succeed in maintaining the persistence of network services and keeping link recovery manual-free. However, this is not enough to bring the municipal

60 WMNs to our daily life. We found that they experienced more link failures than expected during the simulation, and the reason is a common phenomenon in our daily life — that interference sometimes causes vast overlay for its periodic occurrence in urban areas — namely the “loop effect”. Unfortunately, previous works paid no attention on human activities and in turn suffered from the “loop effect” badly.

65 In order to eliminate the “loop effect” and keep the former two conditions maintained simultaneously, we present a mechanism for real-time link recovery with robustness guaranteed and maximum throughput achieved in municipal WMNs named *Anti-Loop Network Reconfiguration System (ALRS)*. The advantages of our work can be summarized as follows:

- 70 • We combine urban characteristics with the interference avoidance in the consideration of link recovery.
- ALRS estimates local urban characteristics as soon as the link failure is discovered, and reduces the occurrence possibility of “loop effect”.
- The network recovery is cost-effective because of the local limitation of topology changes in ALRS.
- 75 • ALRS achieves throughput maximization after the recovery.

The rest of this paper is organized as follows. Section II and III explain relevant concepts and related works. We present the cause and characteristic of “loop effect” in Section IV. The detailed design of ALRS and evaluation results are given in Section V and VI. Section VII concludes the paper.

80

2. MODELs and CONCEPTs

In this section, we first present a brief introduction to the multi-channel multi-radio wireless mesh network system (mr-WMN). Then, several definitions involved in ALRS are explained respectively.

85 2.1. Multi-channel Multi-radio WMN

Multi-channel multi-radio wireless mesh networks, known as mr-WMNs in some papers [11, 12], are thought to be the preferred choice for providing everywhere Internet access with QoS supports. There are two components in mr-WMNs — the mesh nodes and the gateway — in terms of hardware. The router (or AP) plays the role of a mesh node in mr-WMNs, which is responsible for transferring messages to other mesh nodes or the gateway as well as providing Internet access in its signal cover. Con-
 90 trary to wireless transferring, a gateway is connected to the Internet with a wire-line infinite-bandwidth link. A gateway is a mesh node with an extra, interference-ignored, unlimited access to the Internet, in a sense. All the Internet services are essentially
 95 provided by the gateway through multi-hop mesh node paths. An example topology of mr-WMN can be seen in Fig 1.

Figure 1: An Example Topology of mr-WMN

The number of antennas (or radios, radio interface cards) is not restricted on a

mesh node, indicating it is able to maintain several transmissions synchronously. Mesh nodes can communicate with each other if and only if at least one pair of their antennas
100 is working in the same channel.

There are $\mathcal{K}$ orthogonal channels available for the network, as $\mathcal{K}$ can be any positive integer for universality. Actually, the transmission volume of a gateway and the number of antennas on a node are both limited, and there are other serious problems in deploying and utilizing large-scale WMNs(e.g. the interference generated within
105 the network is extremely aggravated and should not be ignored, the giant demand of transmission power, etc.), which will not be discussed in this paper. In this case, although the assumption is unrestricted, our analysis and mechanism are presented under the precondition that the network scale is limited. This is reasonable because the urban WMNs are deployed in terms of blocks and streets at most.

110 2.2. Definition of Several Concepts

2.2.1. link

A gateway is regarded as a mesh node when it is exchanging information with mesh nodes.[11, 12]

If at least one pair of antenna within communication range from two nodes is working in exactly one channel, there is a *link* between two nodes. *Link* is the only manner
115 of transmission no matter in node-node or node-gateway transmission.[13]

2.2.2. link failure

When two nodes fail in transmitting messages as they used to, the link between these nodes is considered to be failed. The cause of a *link failure* is various and the
120 mostly common reasons for the *link failure* are mainly interference & link requirement violation.[11, 12]

2.2.3. throughput

The *throughput* of the network in this paper is the sum of bandwidth that mesh nodes can provide to users [5]. The higher the *throughput* is, the more information
125 users are able to obtain from the Internet.

2.2.4. *transmission & interference range*

When a wireless signal transmission device $\mathcal{A}$ is functioning, all the wireless devices in its *transmission range* [15] are able to recognize the messages that $\mathcal{A}$ sends. In this case, these devices have the ability to communicate with $\mathcal{A}$. But $\mathcal{A}$ also has an
130 *interference range* [16], which is generally more than twice as the *transmission range* and all the devices are influenced within it. In other words, these devices are interfered by $\mathcal{A}$, if they are using the very channel that $\mathcal{A}$ is working on. Interference is bidirectional, and all the participants in interference are influenced equally, which is not acceptable in wireless communication.

135 2.2.5. *priority*

In our mechanism, the gateway is responsible for the network information storage, link quality collection and reconfiguration plan generation. Each link in the network has a list of channels stored at the gateway, indicating its channel *priority*. The *priority* is the faithful reflection of channel performance. The smaller the *priority* is, the better
140 performance the link can achieve on the corresponding channel.

3. RELATED WORK

Wireless mesh network catches plenty of attentions from researchers as a common tool for providing efficient wireless Internet access for citizens. More and more scholars have focused their sights on performance of municipal WMNs. The authors in [9]
145 present a scheme for router deployment in WMN to achieve budget control, connectivity and system robustness simultaneously. A paper [1] focusing on throughput maximization and fair bandwidth allocation in WMNs is also widely cited by other works. There are vast quantities of researches concentrating on quality of service (QoS).

Link recovery is an important research topic in WMN to meet QoS requirements.
150 The performance of wireless mesh network drops down significantly while encountering link failures. Among various solutions proposed for recovery from link failures in WMNs, four categories can be summarized according to their basic ideas. These techniques for link recovery are listed as follows.

3.1. Initial Resource Allocation

155 All the existing works on resource allocation and network deployment in WMNs belong to this category. They mostly offer a network topology or a routing method or a channel assignment to satisfy diverse QoS guarantees.

Among these achievements, Alicherry, Bhatia and Li [5] proposed a representative joint channel assignment solution. Their method takes interference and channel
160 availability into account to formulate channel assignment and routing problem mathematically and efficiently. The advantage of their technique is the maximization of throughput and effective exploitation of the increased number of channels and radios.

A paper based on the natural multi-radio potential of WMNs written by Brzezinski, Zussman and Modiano [17] makes use of the local pooling notion in distributed
165 mechanism accomplishing 100% throughput of the network.

The Initial Resource Allocation algorithms perform optimal and comprehensive on utilizing the advantages of wireless mesh networks. But as a cost of outstanding performance, they mostly require global configuration of the network changes, which makes them inappropriate and inefficient for recovery from link failures.

170 3.2. Interference Aware

Interference aware[18] is also a widely used method for link recovery. Ramachandran et al. [7] put forward a method for solving the problem of interference in multi-radio wireless mesh network. They proposed a novel mechanism for interference definition and a channel assignment protocol based on it. Their system pointed out an
175 insightful interference estimation scheme that could be deployed in all wireless mesh networks.

Inspired by their solution, we modified their idea of interference estimation by taking historical information into consideration for further utilization.

3.3. Greedy Algorithm

180 Unlike Initial Resource Allocation, greedy algorithms in link recovery focus their attention basically on local benefit instead of the global effectiveness. Obviously, greedy methods have lower algorithm complexity than other algorithms by concerning

the vicinity of the faulty link(s) simply. [19] presents a distributed algorithm making dynamic channel assignment according to the traffic loads. It can handle both network link failure as well as traffic load changes simultaneously.

Though so many advantages they have, greedy algorithms suffer from the “*ripple effect*” badly. While recovering from one link failure, greedy algorithms may cause other links functioning regularly fail sequentially, which seriously affects the performance of the whole network.

3.4. ARS & ERS

Kim and Shin [11] give a new method namely Autonomous network Reconfiguration System (ARS) for solving link recovery problem in WMNs. ARS collects information and lists all feasible plans for network reconfiguration when a link failure is detected. Instead of global changing, ARS keeps the changes within a range around the faulty link. Meanwhile, ARS distinguishes the available plans with QoS test to avoid the ripple effect. An optimal plan will be picked by an optimal plan selection method at last. The process can be seen in Fig 2.

Figure 2: ARS Operation Process

Enhanced Reconfiguration System (ERS) [12] is an improvement of ARS by taking the cost of changes into consideration. With the definition of cost of each change in network topology, ERS wisely chooses the optimal plan to make the network recover from link failure at the minimum cost.

Although ARS and ERS have been widely used for link failure recovery, they may suffer terrible experience for characteristic inadequacy in the urban area. While they are trying to make full use of all the resources, the optimal plan selection schemes of ARS and ERS fail in reflecting human activities which guides to a non-optimal (or even worse) plan.

4. LOOP EFFECT

Just like the “ripple effect”[20] is discovered during the practical use, the performance of practical municipal WMN is influenced by rhythmic interferences or requirements. These influences are mainly caused by human activities, such as the aggregation of crowd (the explosion of service requirements and diverse wireless interference), the building under construction (block in the way), etc. These influences share the same property of regularity which is suitable to be solved by machine-learning methods and have a deep relationship with human activities. Existing methods (shown in Section II-
210 I) fail to deal with these influences due to the ignorance of urban characteristic. What’s more, they may lead to repeating link failures and even network collapse. This phenomenon is called “loop effect” in this paper.

The properties of “loop effect” could be summarized as follows:

- 1 “Loop effect” is mainly caused by human activities.
- 220 2 There is regularity within the interferences and requirements brought by “loop effect”.
- 3 Its consequences are mainly link failures.

5. ALRS ARCHITECTURE

In this section, we firstly present an overall introduction and the process of ALRS.
225 Then, a detailed algorithm description is given. The analysis of the algorithms is discussed at last.

5.1. ALRS Overview (*Reconfiguration Process*)

In a mr-WMN in urban area, human activities are more likely to blame for regular interference occurrence. Actively interactions across the link and network layers are the foundations of our real-time and rational design for reconfiguration plan. The statuses
230 of links are detected and collected by a distributed algorithm running on every node and reported to the gateway periodically. The gateway is responsible for storing all the link information respectively and generating corresponding localized reconfiguration plans.

The optimal plan is selected by a scheme deployed on the gateway as well, which will
 235 be sent to all the nodes involved for execution at last.

5.2. The Preparing Algorithms

On deploying ALRS to a mr-WMN, an initial algorithm should be executed at first.
 The gateway has to obtain the topology of the whole network and generate correspond-
 ing priority list for each link (all the priority sort according to bandwidth at the very
 240 beginning). Moreover, all the links connected with the gateway should be allocated
 with the available throughput-maximum channels, which can be achieved by ALRS's
 exhaustive design. Running an initial-resource-allocation algorithm is the final action
 of the initial phase to assign the rest links [10, 17]. The detailed process of ALRS is
 about to be introduced following.

Algorithm 1: Monitoring Algorithm operation at mesh node $i(t_m)$

```

1 for each link  $l_{ij}$  do
2   calculate link quality  $lq_{ij}$  over time  $t_m$ 
3   if link  $l_{ij}$  violates link requirements  $r$  then
4     GFRS-Algorithm(link  $l_{ij}, r, i$ )
5   end if
6 end for
7 send monitoring results  $\{lq_{ij}\}$  to gateway  $g$ 

```

Algorithm 2: Group Formation & Requests Sending Algorithm: GFRS-Algorithm(l, r, i)

```

1 if node  $i$  is the discoverer of the failure on link  $l$  then
2   request a group formation on link  $l$ 
3 end if
4 participate in a leader election if a request is received
5 if node  $i$  is elected as a leader then
6   send a planning request message  $(r, M)$  to gateway  $g$ 
7 end if

```

245 Algorithm 1,2,3 depict the operation of mesh node.

Firstly, mesh nodes are designed to monitor link states at every timeslot t_m (e.g.,
 10s) when the network is functioning normally. All the link states collected should
 be reported to the gateway at the end of t_m cyclically. Secondly, when a link violates

Algorithm 3: Reconfiguration Algorithm(p, t_r)

```
1 if  $p$  includes changes on node  $i$  then  
2   apply changes to links of node  $i$  at  $t_r$   
3 end if  
4 forward  $p$  to neighbors, if any
```

link requirement, the discoverer of the link failure calls for a leader election among
250 local mesh routers that use a faulty channel. The leader node is elected by the bully
algorithm [21] and is responsible for sending the reconfiguration request to the gateway.
At this time, the gateway generates a corresponding reconfiguration plan p according
to its knowledge as a response. Finally, as soon as a mesh node (including the leader
node) receives p and has not applied it yet, it applies the changes and forwards p to its
255 neighbors.

Actually, we could run the leader election algorithm in Algorithm 2 in advance
to make the local leader also the command node as the gateway does, which makes
our mechanism completely distributed. But firstly, this requires storing memory and
relatively strong calculating capability, which is usually not available to a normal mesh
260 node. Secondly, both states transmission and storage lead to further cost since the data
could be collected incidentally with the normal data towards the gateway, which only
requires small additional bandwidth cost. Thirdly, the gateway is much more unlikely
to go wrong than a mesh node. Hence the gateway is preferred to be the commander of
ALRS.

265 5.3. Priority List Update Method

The link states gather at the gateway, where the link qualities and link failure record
are stored separately. The link qualities are used as constraints for feasible reconfigu-
ration plan selection to prevent “*ripple effect*”, which is detailed discussed in [11].

On the other hand, if link l working on channel c fails, the gateway triggers faulty-
270 count module to update the priority list, whose storage structure is shown in Fig 3.

We can assume priority of channel c of link l , latest failure time, continuous failure
count, current time as $p_{l,c}$, $t_{l,c}$, $c_{l,c}$ and $t_{current}$ respectively. These values are stored
at the gateway. When a link l on channel ch is detected failed, the priority list update

Link ID	Channel NO.	Priority	Latest Failure Time	Continious Failure Count
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Figure 3: Priority Storage Information

method is awoken. Firstly, the gateway checks the current time $t_{current}$ and the latest
 275 failure detected time $t_{l,c}$ of link l . If the time interval between these two parameters
 is less than a preset threshold T , ALRS identifies it as a continuous failure. In this
 case, for all the available channels on link l , their counters $c_{l,c}$ s as well as the global
 continuous failure counter $count$ should be increased by 1. Then ALRS updates the
 priority list of link l as $p_{l,c} = p_{l,c} * \alpha * c_{l,c}$, the latest failure detected time list of link l as
 280 $t_{l,c} = t_{current}$. In the formula, α is used for representing the proportion of the original
 priority, indicating the sensitiveness of the mechanism to link failures. Meanwhile,
 the local environmental influence is also considered in ALRS. Since the link failure is
 detected on channel ch , all the priority lists of the links within the interference area of
 link l are updated as well. At this time, not all the channels but only the detected failure
 285 channel ch is concerned, namely $p_{l',c} = p_{l',c} * \alpha * c_{l',ch}$. At last, if continuous link failure
 counter $count$ is discovered larger than a preset threshold $count_{max}$, ALRS identifies
 the link l is not suitable for data transmission any more and calls for a route switch.
 The above process is shown in Algorithm 4.

According to the Algorithm 4, the priority of different channels used by relevant
 290 links are considered comprehensively instead of unilaterally, which is a significant
 improvement achieved by ALRS. The priority $p_{l,c}$ is influenced by not only its own
 link state but also its neighbors operating conditions. Due to the benefit of our design,
 ALRS is more sensitive to local environmental changes than all the existing methods.
 The priority number rises when link failure happens, suggesting the degree of priority
 295 is decreased. Typically, it increases in factorial level if encountering continuous link
 failures no matter on either channel. When the network encounters a link failure, the
 $p_{l,c}$ s of all the links within the scope of interference distance from the failure link are
 updated.

The priority list is the result of sorting by priorities, according to which ALRS
 300 selects the best reconfiguration plan.

Algorithm 4: Priority Update Algorithm(l, ch)

```
1 var count=0
2 for all the available channels  $c$  do
3   if  $t_{current}-t_{l,c}<T$  then
4      $c_{l,c}=c_{l,c}+1$ 
5      $count=count+1$ 
6      $p_{l,c}=p_{l,c}*\alpha*c_{l,c}$ 
7   else
8      $c_{l,c} = 0$ 
9   endif
10   $t_{l,c}=t_{current}$ 
11 endfor
12 for link  $l'$  within interference distance from link  $l$  do
13   if  $t_{current}-t_{l',ch}<T$  then
14      $c_{l',ch}=c_{l',ch} + 1$ 
15      $p_{l',c}=p_{l',c}*\alpha*c_{l',ch}$ 
16   else
17      $c_{l',ch} = 0$ 
18   endif
19    $t_{l',ch}=t_{current}$ 
20 endfor
21 if  $count>count_{max}$  then
22   call for a route switch
23 endif
```

5.4. Reconfiguration Plan Generation System & Optimal Plan Selection

There are three elementary operations that are used to make network topology reconfiguration with QoS guaranteed, namely the channel switch, radio switch and route switch [11, 12].

305 As shown in Table 1, three kinds of operations are exhibited individually. They are the components of the reconfiguration plan. It is a prerequisite that the discovered faulty channel should not be used again. At this time, a channel switch is necessary. Meanwhile, the reconfiguration may need a radio switch since the network topology may be quite different from the original one, and the reconfiguration plan should call
310 for radio switches to maintain the network transmission during the reconfiguration. At the same time, if one link is discovered not suitable for transmission(as shown in Algorithm 4), a route switch is necessary. With these operations, each reconfiguration plan is able to be executed automatically with QoS guaranteed.

Table 1: Formalization of Link Operations

Primitive Changes	Description
Channel Switch ($S(\mathcal{A}_i, \mathcal{B}_j)_{\alpha \rightarrow \beta}$)	Radios $\mathcal{A}_i$ and $\mathcal{B}_j$ of link $\mathcal{A}\mathcal{B}$ switch their channel (α) to channel (β)
Radio Switch ($R(\mathcal{A}_i, \mathcal{B}_j)_{\alpha \rightarrow \beta}$)	Radio $\mathcal{A}_i$ in node $\mathcal{A}$ re-associate with radio $\mathcal{B}_j$ in node $\mathcal{B}$ using channel (β)
Route Switch ($D(\mathcal{A}_i, \mathcal{B}_j)$)	Radios $\mathcal{A}_i$ and $\mathcal{A}_j$ terminate link $\mathcal{A}\mathcal{B}$ and look for a detour path for association

However, the network changes should be limited as locally as possible. Therefore,
 315 we use a parameter $\mathcal{K}$ to describe the scale of network reconfiguration. If there is no feasible reconfiguration plan generated when the network changes are limited within $\mathcal{K}$ hops from the faulty link, $\mathcal{K}$ increases until a feasible plan is found.

Meanwhile, during the generation, QoS check is running all the time to get rid of “ripple effect” [11], which is based on the link information and real-time available
 320 channel airtime. Both of them are contained in the message M shown in Algorithm 2 and collected during the leader election process. The feasible plan generation is illustrated in Fig 4.

Figure 4: ALRS Process

ALRS now has at least one feasible reconfiguration plan which is QoS satisfiable. The gateway has to select an optimal plan if there are more than one. Our goals are
 325 achieving network maximum throughput as well as the min-max priority of all non-gateway links. If any link connected to the gateway is involved in the reconfiguration plan except for calling for a route switch, the maximal available bandwidth channels should be allotted to it. Then the min-max priority can be obtained by selecting the min-

max priority plan according to the priority list introduced in *sub-section 5.3*. When
 330 there is a tie, the plan with fewer changes (namely less cost) will be chosen as the
 optimal plan. We will prove the throughput maximum in *sub-section 5.6*.

While a reconfiguration plan is generating, only the channels that possess no higher
 value than existing max priority are taken into consideration, which absolutely reduces
 the time spent by the plan generation. The existing max priority is infinitely great at
 335 the beginning, and is set to be the max priority after a plan is generated.

5.5. Localized Reconfiguration Plan Execution

The gateway is responsible for sending the reconfiguration plan to the leader elected
 in *Algorithm 3* as soon as the optimal plan is selected. On receiving the reconfiguration
 plan, the leader node needs to forward the plan to all its neighbor nodes and setting
 340 up a time point (namely t_r in *Algorithm 3*) for execution. The mesh node triggers its
 reconfiguration module (seen in *Algorithm 3*) when it receives the information for the
 first time.

5.6. Proof of Throughput Maximum

In a random wireless mesh network, considering the uplink transmission:

345 **Definition 1.** The sets of wireless mesh nodes and gateways (sink nodes) are $N = \{n_i | i \in \mathbb{Z}^+\}$ and $S = \{s_j | j \in \mathbb{Z}^+\}$ respectively. Therefore, the network topology is a directed graph $G = \{N, L\}$.

Definition 2. If there exist a directly wireless data transmission path from node n_i to
 n_j , there is a link $l_{i,j}$ between node n_i and n_j , and the link is called an **outside** link of
 350 node n_i and an **inside** link of node n_j . Its capacity is $c_{l_{i,j}}$.

Definition 3. The set of links is $L = \{l_{i,j} | i, j \in \mathbb{Z}^+, i \neq j\}$.

Considering the bandwidth occupation:

Definition 4. The maximum bandwidth available on node n_i is b_{n_i}

Our objective is to prove $\sum_{n_i \in N} b_{n_i}$ is maximum in our mechanism.

355 **Theorem 1.** *The total throughput achieves maximum in ALRS.*

Proof. For a random node $n_i \in N$, it has inside links $l_{i,j_1}, l_{i,j_2}, \dots, l_{i,j_m}$ and outside links $l_{k_1,i}, l_{k_2,i}, \dots, l_{k_n,i}$, where m and n stand for the number of its inside and outside links. Considering a given time point, the real-time bandwidth occupation of all the inside and outside links of node n_i could be represented as $O_{i,j_1}, O_{i,j_2}, \dots, O_{i,j_m}$ and $O_{k_1,i}, O_{k_2,i}, \dots, O_{k_n,i}$, and at this very time point, the maximum bandwidth node i could provide is

$$b_{n_i} = \sum_{n_j \in N, i \neq j} O_{i,j} - \sum_{n_k \in N, i \neq k} O_{k,i} \quad (n_i \in N) \quad (1)$$

This formula is also correct for other nodes. And if we formulate them and add them together, we could get

$$\sum_{n_i \in N} b_{n_i} = \sum_{s_j \in S, n_k \in N} O_{k,j} \quad (2)$$

Namely the total bandwidth provided in WMN equals to the sum of occupied bandwidth of the links connected to the gateway. This is because except for the inside links of the gateways, other links are both inside links of one node and outside links of another one, making them eliminated in the calculation. In this case, we can get access to the following lemma:

360

Lemma 1. *For uplink transmission, the maximum throughput of a WMN equals to the sum of the capacity of the links connected to gateways.*

It is similar to achieve the same lemma for downlink transmission. In this case, we could come to a conclusion that the maximum throughput of a WMN equals to the sum of the capacity of the links connected to gateways.

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In the initial algorithm (seen in *sub-section 5.2*), the combined capacity of all gateway links achieves maximum, indicating the total bandwidth reaches maximum after initialization.

The topology of the network will not change except for reconfiguration. If the links connected to the gateway are not involved in the reconfiguration plan, the bandwidth maintains optimal. Otherwise, available largest bandwidth channels will be allotted to

370

the links connected the gateway according to *sub-section 5.4*, and the network achieves its available maximum bandwidth either.

To sum up, the total throughput of the network achieves maximum in ALRS during
375 its lifetime. □

5.7. Additional Comments

The complexity of ALRS is reasonable thanks to the distributed and localized design. First, the monitoring module consumes less than 12Kb/s probing bandwidth for each radio. In addition, group formation incurs only $O(n)$ message overhead, where n
380 represents the size of the group. Moreover, the reconfiguration plan generation receives acceptable overhead as the changes are limited locally. Specifically, the optimal plan selection only incurs $O(l)$ complexity, in which l indicates the number of links within $\mathcal{K}$ range from the failed link. Also, the priority list is the only information that needs to be stored at the gateway permanently, which takes $O(l)$ complexity.

385 The design of ALRS is not suitable for large scale WMN(neither is ARS and ERS). In urban WMNs, a gateway is mostly serving a block or even only part of it. This is because it may lead to congestion at the gateway if too many mesh nodes are supported by it. The network also faces higher risk in providing service since a gateway goes wrong will cause a larger scale of service unavailable. In this case, ALRS is practical,
390 and both the collection and storage overhead are acceptable.

6. PERFORMANCE EVALUATION

In this section, we exhibit the performance of ALRS via simulation in large-scale network settings under various conditions to confirm that ALRS is able to detect link failures effectively in the network and achieve self-adaptive reconfiguration. We also
395 compare the real-time throughput of ALRS and other techniques.

The introduction of our simulation environment is given in this section at first. Then we describe the reconfiguration cost and the detailed analysis of the simulation results comes last.

6.1. Simulation Model & Method

Our simulation platform is ns-2 [22], a simulator designed by UC Berkeley. A grid topology is used in which there are 25 nodes in the square of $1 * 1 km^2$. The distance between two adjacent nodes in our topology is 185m. The nodes are equipped with several radios, mainly based on their proximity to the gateway, and the number of radios on the nodes ranges from 1 to 4 randomly. We set the reconfiguration range $\mathcal{K}=3$ as the initial reconfiguration range.

There are several extra nodes in the topology as the interference sources, whose information is not available to the gateway. The interference nodes are randomly placed in the topology and their locations are changing from time to time. Meanwhile, interference nodes are broadcasting messages using either part or all of the available channels indicated by 802.11 protocols during the simulation. The number of radios in each interference node is not limited in our simulation. If an interference node is broadcasting in all the available channels it means there is a block at the very location of the node. The topology of block simulation is shown in Fig 5, in which red links are the influenced links.

Figure 5: Block & Interference Simulation

In the simulation, each node is allotted with a random number around a fixed val-

ue as the traffic load, indicating the UDP flow gathered at the node. Routing policy is determined by the routing protocol multiradio-aware routing metric (WCETT [23]) pre-installed on all the nodes. Similarly, the nodes are also equipped with shadowing propagation model [24] which is used to simulate varying channel quality and multi-
420 path effects.

6.2. Reconfiguration Cost

The reconfiguration cost is presented in two aspects: the number of generated plans and the operation cost of each generated plan. The former is the representation of the cost in the generation phase and the latter reflects the cost of the network changing
425 phase.

As stated in [12], the total reconfiguration cost incurred for each and every plan generated could be formulated by the following formula:

$$C_{R_i} = p\alpha + q\beta + r\gamma \quad (3)$$

In the formula, p is the number of channel switch operations, q is the number of radio switch and r is the number of route detour operations involved in the reconfiguration plan R_i . Values of α , β and γ denote the cost of the channel switch, radio switch and route switch respectively. If there are n plans existing, C_{R_i} is computed and stored
430 for each and every plan.

Indicated by [12], the values of α , β and γ are set to 5,7,10 respectively, and the costs of various combinations of primitive link changes involved in each plan are exhibited in Table 2.

The columns CS, RdS and RtS denotes the number of the channel switch, radio
435 switch and route switch respectively. C_{R_i} indicates the total reconfiguration cost. Since the priorities of the same channel on different nodes are different, all the three operations are involved with priority change. In this case, the maximal priority involved in the reconfiguration plan is represented as MP in the table.

The objective of ALRS is to achieve maximum throughput with min-max priority
440 of each link and we select the optimal plan by picking out plans with minimum MP

Table 2: Configuration Cost for Feasible Plans

No.	CS	RdS	RtS	C_{R_i}	MP
1	1	0	0	5	4
2	0	0	1	10	3
3	1	0	1	15	2
4	2	1	0	17	3
5	0	1	2	27	2
6	3	0	0	15	4
7	0	0	3	30	3

value. It is shown in Table 2 that plan 3 and 5 share the same MP and as we stated in Section V the plan with less cost is chosen as the optimal plan. In other words, plan 3 is the optimal plan generated by ALRS with the cost 15.

In order to evaluate the cost of ALRS we make a comparative trial which is shown in Table 3.

Table 3: Cost Comparison

Method	Num of Feasible Plans	Optimal Cost (C_{R_i})
ARS	16	36
ERS	16	15
ALRS	7	15

445

We tested the performance of ARS, ERS and ALRS respectively with the same simulating environment. One link is influenced and failed. The locations of nodes and gateways remain all the same and the reconfiguration range is set to 3. We recorded the number of generated plans (namely feasible plans) and the optimal one for comparison.

450

ARS and ERS both generated 16 feasible plans due to the exhaustive method while ALRS only generated 7 feasible plans. The cause of this phenomenon is that ALRS eliminates overlarge priority involved plans during the generation phase for saving time as we described in Section V. But the gateway involved reconfiguration plans are not influenced by this action and the throughput maximization is not impacted according

455

to our proof. On the other hand, the min-max priority is not influenced apparently.

We calculated the costs of the optimal plans generated by all three methods as well

and the result is shown in Table 3 too. ARS has not considered the cost of reconfiguration as the result indicates. ERS and ALRS share the same cost of the optimal plan because they selected the same optimal plan actually, and of course at a lower cost.

460 There is possibility that the optimal plan generated by ERS is eliminated at the beginning of ALRS, and at that time a “sub-optimal” plan (in the view of cost) will be selected by ALRS. But the “sub-optimal” plan possesses higher maximal throughput or lower min-max priority which indicates less possibility of link failure in the future with no doubt due to the explanation of “loop effect”. In this case, there is a trade-off

465 among throughput, robustness and minimum cost and which one to choose is a matter of opinion and conjecture.

Due to the fact that the feasible plans generated by ALRS are not all-inclusive, it is unavoidable that there are some situations under which the optimal plan selected by ERS is eliminated by ALRS during the feasible plan generation phase. But except

470 for the “loop effect”, the behavior of the priority list achieves the same results as the cost analysis because well-performed and cost-effective channels are going to be given higher priorities. In this case, ALRS shares considerable possibility in generating the same optimal plan with ERS when “loop effect” is not occurred. On the other hand, faced with the “loop effect”, ALRS outperforms ARS and ERS in efficiency, throughput and robustness. As a conclusion, ALRS possesses a large possibility in performing

475 no less than ERS, let alone ARS.

6.3. Evaluation Result

This subsection presents the performance and analysis of ALRS. Available bandwidth and the probability of failure’s occurrence are mainly considered in the evaluation.

480 All the evaluation results are calculated as average values of 50-100 times of experiment.

6.3.1. Throughput during recovery from one failure

We first test our mechanism in traditional WMNs. In this case, the main cause of link failures is the unpredictable interference. As shown in Fig 6, ALRS outperforms

485 ARS, ERS and greedy method both on throughput and recovery time. Due to the

Figure 6: Real-time Throughput during Recovery from one failure

carefully designed mechanism, ALRS takes less time in generating feasible plans and achieves maximum throughput after reconfiguration.

When a failure happens, all of techniques we tested in the simulation experience rapid decrease on throughput performance. Note that ARS, ERS and ALRS almost re-
490 bound simultaneously while the Greedy method falls behind. However, ALRS actually experiences the fastest reaction time but not revealed in the figure due to the interval sampling. This is because ALRS generates relatively less reconfiguration plans than ERS and ARS. And that ALRS outperforms ARS and ERS on throughput reflects this fact in a way.

495 6.3.2. Throughput during recovery from multiple failures

It is a core promise of ALRS to deal with the continuous link failures, namely the “loop effect”. In order to evaluate its performance on avoiding the “loop effect”, we also arranged simulations on recovery from multiple continuous failures. As shown in Fig. 7, the performance of all four techniques when multiple link failure happened in a
500 line is exhibited. Except for ALRS, the other three techniques all experience oscillating throughput. This is due to the fact that their designs are focusing on the recovery from one link failure. And unfortunately, they either generate an unsuitable plan for the subsequent failure recovery or get confused by the conflict of several reconfiguration plans. On the other hand, ALRS takes the priority into consideration, which actually
505 reflects the subsequent failures that may be coming. As a result, ALRS recovers from

Figure 7: Real-time Throughput during Recovery from multiple failures

the multiple failures more quickly.

Notably, there are situations when ARS and ERS outperform ALRS (e.g. the time point when the third failure happens in Fig. 7) in our simulation. This phenomenon could be seen in single failure recovery simulations every now and then. Although the number of reconfiguration plans generated in ALRS is no more than that in ARS and ERS, there are cases that they generate the same plans. At this time, ALRS should further consider the priority issues while ARS and ERS do not. Consequently, ARS and ERS outperform ALRS under such situation. However, Fig. 6 and 7 exhibit the average performance among plenty of simulations, and we could come to the point that ALRS outperforms the other techniques in general. But this is not an absolute conclusion in every situation.

6.3.3. Throughput on the number of global channels

The average throughput achieved after recovery from multiple failures on the number of global channels is also evaluated among the simulations, as shown in Fig 8. Although ARS and ERS are not good at dealing with multiple failures during the recovery process, they may achieve good throughput performance after the reconfiguration, if there is only one faulty channel. However, they experience poor performance on throughput after recovery as the number of global channels increases. This is mostly due to the conflict of their chaotic reconfiguration plans on multiple channels. ALRS experiences the best performance not only during the recovery process, but also after

Figure 8: Average Throughput after Recovery from Multiple Failures on the Number of Global Channels

it.

6.3.4. The performance on avoiding “loop effect”

We also summarized the times of link failures on the number of global channels in the simulation. It is obvious that ALRS beats the other three techniques on “loop effect” avoidance. The result could be seen in Fig 9.

According to Fig 8 and 9, ALRS is able to make more flexible reconfiguration plans with more available channels. It considers the potential of future failures that may come and tries to avoid them during the reconfiguration plan generation. Since the plan with maximal throughput and min-max priority is chosen as the optimal plan, ALRS does not discriminate against the route switch operation. While on the other hand, the more channels there are, the less possible ARS and ERS choose to use a route switch, which makes the network suffer badly from the “loop effect”. To sum up, ALRS efficiently avoids the “loop effect” and is able to achieve at least equivalent

Figure 9: The Times of Link Failures on the Number of Global Channels

performance in general in the contrary with ARS and ERS.

540 6.4. Data Analysis

According to Fig 6,7,8, ALRS outperforms all the other competitors on the average throughput no matter during or after the reconfiguration, which means ALRS is more suitable for guaranteeing service continuity. Meanwhile, ALRS makes a significant contribution to practical use of municipal WMN due to the avoidance of the “loop effect”, which is shown in Fig 7,8,9. Thanks to the design of priority, ALRS is more
545 adaptive in dealing with severe and volatile interference.

6.5. ALRS's Advantages

In this section, we compare and analyze the performances of ARS, ERS, ALRS and Greedy on throughput achievement and frequent link failures cause by “loop effect” avoidance. ALRS exceeds the other three methods on throughput after recovery,
550

average throughput during reconfiguration, recovery efficiency and robustness. ALRS experiences the least rebound time in all the simulations, and encounters the least link failures.

The relationship between the performance and the number of global channels is discussed in the simulation as well. ALRS achieves outstanding performance with several
555 channels available and avoids the frequent link failures caused by “loop effect”, which influences the performance of ARS and ERS, especially with more global channels.

The cost of ALRS and its comparison with ARS and ERS are considered and discussed, and ALRS takes the least time in generating feasible plans and possesses considerable possibility in achieving optimal cost in reconfiguration.
560

Although the objective of ALRS is to achieve maximum throughput and the avoidance of “loop effect”, ALRS performs perfectly in dealing with normal occasional link failure as well.

7. CONCLUSION

In this section, we will give a brief summary of our work and experiment. Then we
565 will discuss some future work.

7.1. Work Summarize

We propose a scheme for municipal link recovery called “Anti-Loop Reconfiguration System” in this paper. Two techniques namely ARS and ERS have already
570 achieved self-adaptive reconfiguration, but the ignorance of “loop effect” makes them unsuitable for municipal use. ALRS not only overcomes the “loop effect”, but also takes throughput maximum into consideration, both of which make ALRS outperform all the existing techniques and the best choice for municipal WMNs. Moreover, ALRS is not limited by the number of antennas in the mesh node, thanks to which we are able
575 to deploy ALRS to any existing wireless mesh network breezily.

In our experiment, we achieved dramatic experimental results on calculating average performance. But we have to declare that our scheme cannot exceed other techniques in each single simulation. Moreover, the greedy method which can be viewed

as the worst technique in the experiment may experience the best performance under
580 particular simulations, due to the uncertainty of the network and interference around
the laboratory.

We are convinced that the average performance is the loyal reflection of techniques
because of our carefully designed simulation.

7.2. Future Work

585 Besides throughput, more QoS constraints will be taken into account for link recovery
research such as delay, packet loss rate, etc. Meanwhile, other reasons except for
block and interference which may cause “loop effect” are also attracting us for further
study.

In wireless mesh networks, there are more and more studies working on flow level
590 as the trend of delicate management rises, inspired by which, we are curious in re-
formulating the link recovery problem on flow level with continuity of transmission
guaranteed. We will carry on looking for the advantages of flow management and its
reflection in link recovery.

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