Elastic Channel Utilization Against External Radio Interference on SDN-Enabled Multi-Radio Wireless Backhaul Networks

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Elastic channel utilization against external radio interference on SDN-enabled multi-radio wireless backhaul networks

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***Abstract*—This paper tries to avoid a radio interference while effectively utilizing the resource of interfered channel on SDN-based wireless backhaul networks (WBNs). The densification of small cells on wireless networks is required to handle a lot of traffic for the cloud-based ICT services but inevitably needs a WBN to provide network connectivity at every cell. Since most traffic is delayed or dropped once a WBN suffers from an radio interference coming from outside of the WBN, it is general to avoid using the interfered channel or switch a route spatially. Although such countermeasures are effective to avoid an external radio interference, it could be less effective in terms of resource utilization because the interfered channel may still remain resource. From this perspective, we propose a method that estimates the residual resource of interfered channel and uses it as much as possible while avoiding the effect arising from the radio interference. Specifically, our proposed method uses the information about incoming/outgoing traffic to estimate the residual resource and migrate a part of traffic to another channel until the amount of incoming traffic and that of outgoing packets are balanced (i.e., the channel is not a bottleneck anymore). The experimental results showed that our method is able to estimate the residual resource of interfered channel and effectively use it even under external radio interference.**

***Keywords*—Radio interference, OpenFlow, multi-radio, wireless backhaul networks, SDN, WLAN, WMN**

I. INTRODUCTION

Popularization of mobile/smart devices are significantly increasing the demand for wireless communication. Most devices connect with wireless networks and receive/send a lot of data for various cloud-based ICT services such as storage, video and so on. Wireless networks are expected to carry such cloud traffic in time but congestions inevitably occur due to the increased traffic.

The densification (i.e., massive deployment) of small cells is expected to be a solution to handle a large amount of cloud traffic. This brings better spatial reuse of wireless resources and increases the potential capacity of wireless access networks. However, since wiring huge number of cells is unrealistic scenario, the massive deployment of small cells inevitably requires wireless backhaul networks (WBNs) that could become another bottleneck. In a WBN, each of access points (APs) establishes wireless links with nearby APs and relays all traffic by a multi-hop manner until reaching a wired network. In this architecture, the traffic from/to the wireless access networks concentrates on a WBN and creates a bottleneck when a channel overflows with traffic sent by either an AP or some nearby APs.

The traffic distribution is a dominant solution to avoid such bottleneck and was already studied in two approaches [1], [2]; assigning different (orthogonal) channels to nearby APs distributes traffic to multiple channels and a routing technique apportions traffic to multiple paths spatially. Our previous studies [3], [4] also tried to avoid the bottleneck but employed a novel approach; we assign same multiple channels to all APs — all APs establish a wireless link with neighboring APs through every assigned channel, thereby having multiple wireless links — and distribute traffic to the multiple links on every hop so as to avoid the overload of either link (either channel). This approach does not avoid an interference on any channels but instead provides flexibility on selecting channel on each hop. Hence, although the existing studies need to spatially detour traffic to exploit channel diversity, our approach could exploit channel diversity only by performing traffic management on the shortest path without any detours.

Since an AP shares the resource of all channels with multiple APs within its radio range in our architecture, the WBN has to handle traffic so that the total amount of traffic transmitted on every channel is kept less than the channel capacity. Nevertheless, any channels should not have the residual capacity to gain network performance as much as possible. For this purpose, as an underlying technology, we employed SDN that enables to handle traffic quite flexibly. SDN decouples the control plane, which collects the whole network conditions and makes the network forwarding decisions, from the data plane, which devotes to forward data traffic in small (flow) granularity by following the decisions made by the control plane. Then, we could precisely control the channel usage considering the transmission of multiple APs inside a radio range, thereby handling internal radio interference of the WBN. However, none of existing studies including ours is sufficient to handle a radio interference from outside of the WBN.

In case of such external radio interference, an interfered channel often remains the capacity but is not used. To transfer the large amount of traffic, the residual capacity has to be used efficiently even under any interference situations. From this point, we propose a SDN-based method that avoids an external radio interference but utilize the remaining resource of interfered channel to gain the network capacity as much as possible. We first attempt to find the occurrence of external radio interference and then estimate the residual capacity of interfered channel. After that, we design a method that effectively utilizes all channels including an interference channel.

II. RELATED WORKS

Existing studies already tackled to avoid a radio interference but most of them focus on an internal radio interference [5]–[7]. These studies assume that the number of available channels is more than the number of radios on each AP and try to reduce the effect arising from an internal radio interference by channel assignment and/or routing as much as possible. Some studies use SDN-enabled WBN but focus on routing technique distributing traffic spatially [8].

Since it is hard that the network observes the occurrence of an external radio interference, wireless measurement was required. Some studies measure the wireless condition and try to avoid the effect arising from external radio interference [9]–[11]. In paper [9], each AP analyzes measured packets and evaluate every channel in terms of the number of interference sources and the channel usage. A central server collects the analyzed data and allocates channels while avoiding to use interfered channels. In the work [10], an AP measures a signal strength with channel usage and choses a channel that has a strong signal as well as clear condition. In paper [11], an AP measures the busy ratio of channel and avoid a channel that has more than certain level of busy ratio even it still has residual capacity.

As described above, existing studies generally try to find a channel suffering from external radio interference and avoid to use it. However, an interfered channel often remains the capacity according to the degree of radio interference. It is hard to measure it as well as control the traffic while avoiding the overflow on the channel. In this study, we tackle to use the residual capacity as much as possible by exploiting the flexible traffic management mechanism of SDN.

III. SDN-ENABLED MULTI-RADIO WBN

In the previous studies [3], [4], we proposed a SDN-based multi-radio WBN and a traffic management method, called FAM, to increase the network capacity by efficiently utilizing channel resources. Before describing the proposed method of this paper, which is based on FAM, we briefly introduce the architecture and FAM to make it easily understandable.

A. SDN-enabled WBN architecture

We proposed a WBN architecture that enables to use multiple channels simultaneously on every hop as shown in Figure 1 [3]. The WBN is constructed by multiple virtual APs (VAPs) in which a set of physical APs is connected by Ethernet in a daisy-chain manner and each of APs uses a single but different channel for WBN. Since each VAP establishes a wireless connection with neighbor VAPs over every channel in advance — each VAP has multiple wireless links with a neighboring VAP —, the WBN has a potential to control the channel usage if it can dynamically handle traffic over multiple paths. For this purpose, we employed SDN. SDN enables us to dynamically switch transmission paths for data traffic in small (flow-level) granularity, which is generally identified by a 4-tuple (a combination of source/destination IP addresses and port numbers). Thus, we can dynamically control the channel usage on it.

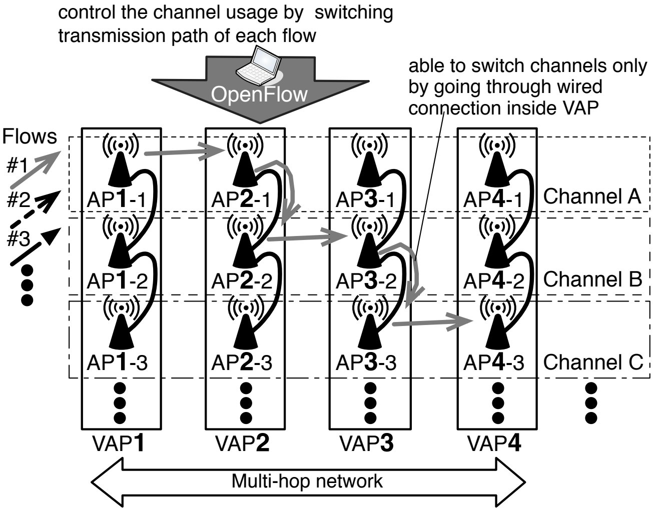


Fig. 1. SDN-enabled multi-radio WBN

We used OpenFlow as a SDN protocol. OpenFlow consists of a controller (OFC) and switches (OFS). A centralized OFC determines control rules, called flow entries (a pair of flow identification and action), and then registers them to OFSs (APs). An OFS handles each flow by following the rules. Whenever an OFS receives unknown packets (i.e., the packet does not match any flow entries), the OFS reports it to the OFC. The OFC adaptively determines a new flow control rule.

B. FAM: flow aggregation method for efficient multi-channel utilization

We proposed a channel utilization method, called Flow Aggregation Method (FAM), to increase the network capacity [4]. FAM uses channels one by one and gains the network capacity as much as possible. More specifically, when new flow arrives at the WBN, an OFC temporarily forwards the arrival flow to a channel (wireless link) having the largest remaining capacity, called transient channel. Since the amount of data traffic of the flow cannot be identified at the time of arrival, the flow may cause packet losses due to a shortage of channel capacity if the flow is transmitted on a severe channel with few remaining capacity. Hence, the utilization of transient channel contributes to prevent packet losses immediately after the arrival timing. Then, since the OFC can measure the required bandwidth for the flow by collecting a statistical information of it — the OFC obtains FlowStats, which includes cumulative values of the number of transferred packets and the amount of transferred bytes, twice in a specific period from every OFS and calculate their difference —, it migrates the flow to a channel having the fewest but larger capacity than the bandwidth of the flow, called aggregation channel. In this way, FAM packs flows into specific channel(s) (i.e., aggregation channels) and uses their resources effectively, thereby increasing the network capacity while avoiding packet losses.

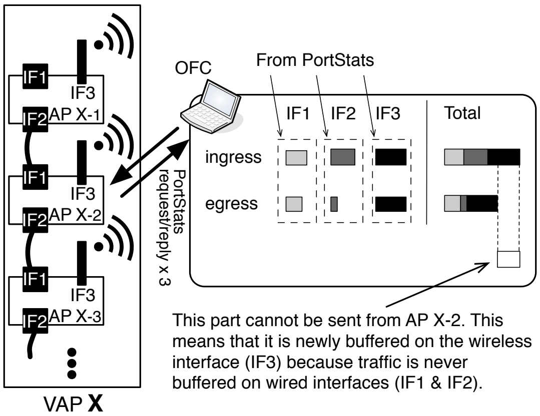
In the above procedures, FAM uses Airtime as a performance measure for both the bandwidth of flow and network capacity to adapt the difference of physical data rate. It indicates time spent for transmitting data during a predetermined time unit. The network capacity can also be shown by total time that could be spent for transmitting data. To measure Airtime, FAM collects statistical information (FlowStats) for each flow. Since FlowStats contains the number of bytes and packets of each flow, FAM calculates Airtime by combining them with physical data rate, which is obtained independent to OpenFlow protocol.

IV. EFFICIENT UTILIZATION OF INTERFERED CHANNEL

We propose a method that efficiently utilizes the residual capacity of interfered channel under the situation of external radio interference. When external radio interference is caused, all flows transmitted near its source are suppressed. Especially in FAM, severe drops or delays happen once it is caused on an aggregation channel because FAM attempts to use the resource of an aggregation channel completely and suffers quite severe congestions at the interference situation. Thus, its occurrence has to be detected as soon as possible and accordingly moves flows onto other channels to avoid it. Here, we first describe how to detect an external radio interference in Section IV-A and how to estimate the residual capacity of interfered channel in Section IV-B. Finally, we show how to handle flows on interfered channel based on the estimated residual capacity in Section IV-C.

A. Detection of the occurrence of external radio interference

Since the occurrence of external radio interference can be noticed only after its effect appears on the traffic condition, we employ a SDN-based monitoring of buffered traffic that will be transmitted on a channel. In case of interference, all traffic cannot be transferred on the interfered channel due to drops (and retransmissions) or a congestion avoidance mechanism. A part of traffic must be newly buffered on a wireless interface. If we assume that both the ingress traffic rate and the degree of interference are kept constant, the amount of newly buffered traffic during a certain period is in proportional to the degree of radio interference. We then try to find external radio interference by the amount of newly buffered traffic.



This part cannot be sent from AP X-2. This means that it is newly buffered on the wireless interface (IF3) because traffic is never buffered on wired interfaces (IF1 & IF2).

Fig. 2. Monitoring the increment of bufferd traffic based on PortStats

We monitor the amount of buffered traffic by exploiting SDN (Figure 2). SDN can collect a statistical information, called PortStats, which includes the cumulative amount of received (ingress) bytes and that of transmitted (egress) bytes on an interface. For monitoring the amount of buffered traffic, we obtain PortStats of every interface periodically — one second interval in this paper — and normalize it by calculating the increment since the previous PortStats. In our WBN, every AP in a VAP has a wireless interface associated with a different channel and also has a few wired interfaces. All traffic arriving at an AP must go to another AP in a VAP over a wired interface or go to another VAP over a wireless interface. Also, since a wired network dedicated to connect APs in a VAP has larger capacity than a wireless network, packets are never buffered on a wired interface. Hence, we subtract the total amount of ingress bytes from that of egress bytes on an AP as shown in Figure 2 and treat the result as the amount of newly buffered traffic on the wireless interface. If the amount of buffered traffic grows without increase of network loads, external radio interference can be detected.

However, miss-detection of radio interference may happen because of inevitable measurement errors of PortStats. To obtain PortStats, an OFC sends one request per interface to an OFS (AP) and the AP replies them one by one, thereby causing a gap of PortStats on every interface. Also, although the OFC sends them in a fixed interval, a reply interval deviates from the request interval due to network delay and/or processing delay of the request. In such cases, we need to distinguish whether the amount of buffered traffic is diverted from measurement errors or radio interference. To handle this, we use two thresholds, T1 and T2: T1 is to find an an event, which is clearly from radio interference, and T2 is to differentiate radio interference from measurement errors.

To identify T1 and T2, we conducted a preliminary experiment; while an OFC measures the amount of buffered traffic by PortStats, constant traffic is transmitted on a point-to-point WLAN using a clean channel, i.e., no radio interference. We collected 10,000 samples of the amount of newly buffered traffic, which is measured in one-second interval. For T1, we use Chebyshev's inequality. When let X is a random variable with finite expected value μ and finite non-zero variance σ^2, for any real number $k > 0$,

$$Pr\Big(|X - \mu| \geq k\sigma\Big) \leq \frac{1}{k^2}. \tag{1}$$

In our case, this equation means that the possibility that the amount of buffered traffic is not between $\mu - k\sigma$ and $\mu + k\sigma$ is less than or equal to $1/k^2$. Also, since the amount of buffered traffic should be a plus number to be used for the interference detection, equation 1 can be

$$Pr\Big((X - \mu) \geq k\sigma\Big) \leq \frac{1}{2k^2}. \tag{2}$$

Since the experiment has no radio interference, μ must be 0. We also obtain $\sigma = 52600$ from the collected samples. Regarding to k, if we assume that a measurement error once an hour can be applicable — this assumption depends on performance requirement —, we get 42.4 by calculating $1/2k^2 = 1/3600$. From these, we can calculate T1 as

$$T1 = \mu + k \times \sigma = 2,223,000 \text{ (bit)}. \tag{3}$$

To address T2, we investigate characteristics of measurement errors. We found in the experiment that the amount of buffered traffic must become smaller after it increases (i.e., measurement error occurs). Since the amount of buffered traffic is increased steadily immediately after a radio interference occurs, we focus on two consecutive results, both of which are larger than T2. To identify T2, we also use Chebyshev's inequality. Before it, we conduct a preprocessing of collected samples; we choose two consecutive results of Nth and $N+1$th results, both of which are a plus number. If the $N+1$th value is larger than the Nth value, we set Nth value to the $N+1$th value. After finishing this throughout all samples, all samples that are not modified are set to 0. We use them in Chebyshev's inequality as like T1. we get $\sigma = 3000$ from the modified samples. Note that, since we cannot expect μ in this case, we calculate it by modified samples and get 501. Then, T2 can be calculated as 127,701 bit from same equation 3 of T1. Nevertheless, since a packet is basically larger than 1,000, we round it off and use 128,000 bit as T2.

From above discussion, an OFC detects the occurrence of external radio interface as follows. Once the amount of newly buffered traffic is larger than T1 (2.223 Mb), it is immediately treated as a radio interference. If the amount of newly buffered traffic is consecutively larger than than T2 (0.128 Mb), it is detected as a radio interference.

B. Estimation of the residual capacity of interfered channel

After an external radio interference occurs, we need to understand how much the capacity of interfered channel is still available to keep using it as much as possible. To estimate the residual capacity of interfered channel, we use the amount of newly buffered traffic because it is highly related to the residual capacity of interfered channel. Since it is already collected at the detection of radio interference in Section IV-A, the estimation is conducted immediately after the detection.

Before an external radio interference occurs, all traffic can be transferred on a channel if it does not exceed the channel capacity. Once an external radio interference occurs, a part of traffic cannot be transmitted and will be buffered because of scarce resources caused by the interference. This implies that the WBN carries all traffic even under radio interference if the total amount of traffic is reduced by the same amount as the buffered traffic. Thus, we simply treat the amount of newly buffered traffic as an excess load and the amount of transmitted traffic as a residual capacity. It is updated whenever an external radio interference is detected by the procedures of Section IV-A.

C. Flow management on interfered channel

When an external radio interference occurs, the proposed method migrates a part of traffic to other channels in flow granularity based on FAM until the traffic going through the interfered channel does not suffer from the interference, i.e., traffic is not newly buffered. This means that the method enables the WBN to effectively utilize the residual capacity of interfered channel. This procedure is performed immediately after the detection of external radio interference (Section IV-A) with the estimation of residual capacity (Section IV-B) is finished.

This method migrates a flow(s) transmitted on the interfered channel to another channel until the total amount of chosen flows exceeds the amount of newly buffered traffic. Specifically, the OFC tries to find a flow that is the smallest but exceeds the amount of newly buffered traffic based on Airtime of every flow, which is collected periodically by FAM. If the OFC found nothing, it next chose several flows in descending order until the total amount of chosen flows exceeds the amount of newly buffered traffic. Then, the OFC migrates selected flow(s) one by one to a channel (it is conducted in descending order of flow volume if there are multiple flows being migrated). At this point, OFC selects a channel, which provides more capacity than the flow volume but the least available capacity, for every flow.

V. PERFORMANCE EVALUATION

In this section, we evaluate the proposed method in a real environment. Section V-A shows the experimental environment and two different scenarios we perform. We then describe the experimental results of two scenarios to show the effectiveness of the proposed method in Section V-B and V-C, respectively.

A. Experimental settings & scenarios

Figure 3 shows the experimental environemnt in which we build a WBN with a single-hop 2-radio WBN. We used Buffalo WZR-HP-AG300H as a physical AP and install OpenWrt with Open vSwitch software, which is an OpenFlow switch implementation, to each AP. Each of APs is placed 0.7-meter apart from each other and APs in a VAP is connected by 1Gbase-T Ethernet. In VAP, we use IEEE802.11a with fixed 54 Mbps on 116 and 132 channels. An OFC connects to OFSs by 1Gbase-T Ethernet because building a control network is beyond the scope of this paper. To generate traffic, we

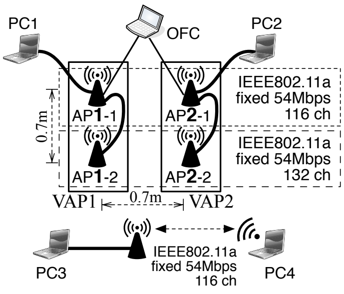


Fig. 3. Experimental environment

prepare two PCs (PC1 and PC2) and connect them to VAP1 and VAP2 by 1Gbase-T Ethernet, respectively. To cause radio interference, we place an additional WLAN in which two PCs (PC3 and PC4) communicats through an AP. We use IEEE802.11a with fixed 54 Mbps on 116 channel for this WLAN.

In this environment, we performs two experiments of different scenarios. In scenario 1, PC1 transmits 51 UDP flows in 3-second interval to PC2. Each flow is generated in 1 Mbps with 1,500-byte packets and kept until the experiment ends. At the 5 second after these flows start, PC3 starts to send a flow with 5 Mbps to PC4 to create an external radio interference. This experiment ends in 200 seconds later. Since the channel capacity is 28 Mbps in the effective throughput, all traffic including the interference $(1\,\mathrm{Mbps} \times 51 + 5\,\mathrm{Mbps} \times 1 = 56\,\mathrm{Mbps})$ could be transmitted by using two channels in this case. Thus, in this scenario, we show that the method can accurately estimate the residual capacity and appropriately migrate flows. In Scenario 2, we first generate the radio interference by PC3 and, at 5-second later, PC1 starts to send 51 flows as like scenario 1. In this scenario 2, we show the effectiveness when flows start to use the already interfered channel although an external radio interference is detected only if the traffic suffers from it.

B. Scenario 1: on a channel that will be interfered

We perform a experiment following scenario 1 for 9 times and compare the proposed method with FAM. Table I shows the total number of lost packets and its ratio in percent. From the table, we can see that FAM drops around 5 percents of packets while the proposed method does not drop any packets. This is because FAM does not notice the external radio interference and keeps using the interfered channel. Specifically, Since FAM controls transmission paths of each flow on every AP only by considering internal radio interference, it tries to completely use a channel even suffering from external radio interference, thereby dropping packets. On the other hand, the proposed method can handle an external radio interference by employing the mechanisms described in Section IV. Once it finds the external radio interference, the method reduces the amount of traffic going through the interfered channel so as to balance it with the residual capacity of interfered channel, thereby preventing packet losses. Also, since the detection is based on the buffered traffic, which is not dropped yet, the number of lost packets could be zero by moving flow immediately after the detection.

TABLE I
NUMBER OF LOST PACKETS CAUSED BY EXTERNAL RADIO INTERFERENCE

	FAM		Proposed	
	# of losts	Ratio	# of losts	Ratio
Maximum	40245	7.44%	0	0%
Median	30883	5.71%	0	0%
Minimum	22746	4.21%	0	0%
Average	31126	5.75%	0	0%

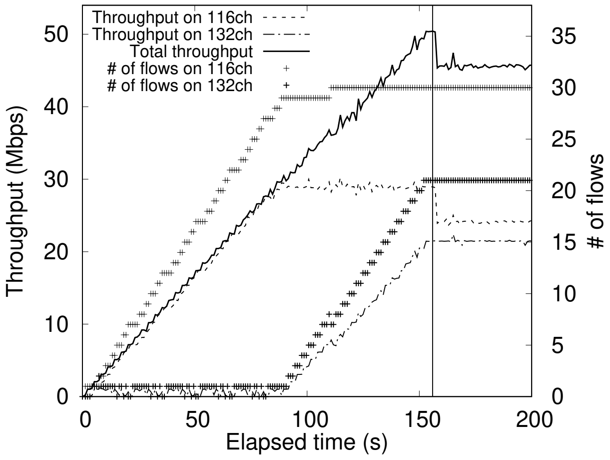


Fig. 4. Time series behavior of FAM

Figures 4 and 5 show the time series behavior of throughput and the number of flows on each channel. The median result of Table I is used for these figures. Compared Figure 4 with 5, throughput on 116ch degrades in FAM after an external radio interference occurs at 155 seconds, whereas the proposed method keep it. Although the proposed method momentary degrades throughput at the occurrence of interference, it returns soon after some flows are moved onto 132ch. Regarding to the buffer, we can see from Figure 6 that T1 appropriately works to find interference as well as T2 successfully prevent unnecessary detections due to measurement errors. From above results, we can say that the proposed method can efficiently use all channels including interfered channel when an external interference suddenly occurs.

C. Scenario 2: on a channel that is already interfered

We next conduct scenario 2 for 9 times. Table II shows the amount of lost packets in FAM and the proposed method. As compared with Table I, Table II has more packet losses in both methods. Since both methods handle a new flow in a same way — they send a new flow in a transient channel —, the flow inevitably loses packets if the radio interference occurs on that channel. Even the proposed method sometimes suffers from it. At the arrival of new flow, the proposed method needs to wait for completion of measuring the flow to appropriately move the flow. Since it takes few seconds, some packets are dropped due to buffer overflow or failed retransmissions. However, the proposed method can limit the lost because it can avoid the

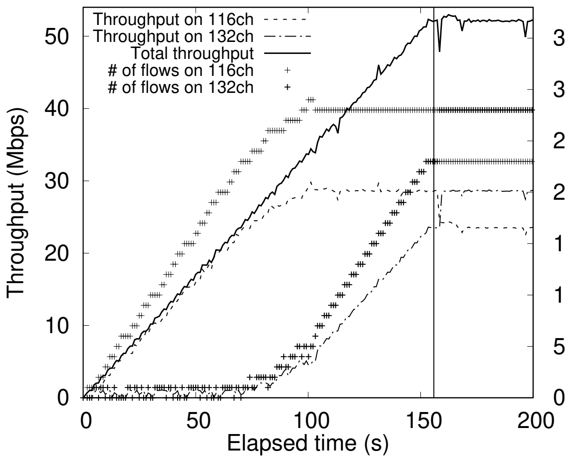


Fig. 5. Time series behavior of proposed method

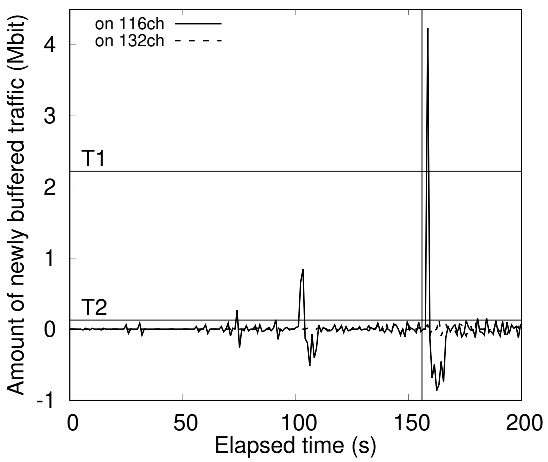


Fig. 6. Amount of newly buffered traffic of proposed method

interference soon once it detects the interference. From these results, we can say that the proposed method can use a channel, which is already interfered.

VI. CONCLUSION

This paper proposes an elastic method that efficiently utilizes channels including channels interfered by outside of WBN. First, we propose how to detect an external radio interference by measuring the amount of newly buffered traffic. Since it contains measurement errors, we use Chebyshev's inequality to appropriately determine two thresholds. The first threshold is to find an event, which is clearly caused by radio interference. The second one is to differentiate radio interference from measurement errors. Then, we estimate the residual capacity based on the amount of buffered traffic measured at the detection and move (a) flow(s) from an interfered channel onto another channel until the traffic does not suffer from the interference. In the experiment, we showed that the proposed methods can appropriately avoid a radio interference as a result of using the residual capacity of interfered channel. Also, two thresholds work well to avoid miss-detections of radio interference with high accuracy. As a future plan, we will handle multi-hop WBN, which has both internal and external radio interference. Also, we will address the problem of how to find and use a channel, which was interfered but is currently clean.

TABLE II
NUMBER OF LOST PACKETS ON ALREADY INTERFERED CHANNEL

	FAM		Proposed	
	# of losts	Ratio	# of losts	Ratio
Maximum	62858	11.62%	622	0.11%
Median	57794	10.68%	0	0%
Minimum	50541	9.34%	0	0%
Average	56882	10.52%	149	0.02%

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