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Sub-1 GHz Coexistence Using Reinforcement Learning based IEEE 802.11ah RAW scheduling

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Abstract: With the increasing demand in outdoor IoT applications such as smart utilities, LPWAN (Low Power Wide Area Network) operating in the Sub-1 GHz frequency band is gaining attention. IEEE 802.15.4g, LoRa and SigFox based devices are already deployed in the market. In addition, IEEE 802.11ah is promising for the smart home applications with consumer devices and systems. Accordingly, the use cases such as smart utility and smart home where many IoT devices are connected will increase, and the coexistence of multiple wireless systems will become a challenge. We propose a method to reduce mutual interference between IEEE 802.15.4g and IEEE 802.11ah by applying reinforcement learning to the IEEE 802.11ah RAW scheduling. Results shows that our proposed method improves packet delivery rate of IEEE 802.15.4g by 7 % without significant degradation of IEEE 802.11ah packet delivery rate.

Keywords: Coexistence, Consumer Device, IEEE 802.11ah, IEEE 802.15.4g, Internet of Things, RAW

1. Introduction

Internet of Things (IoT) enables to process, transform, analyze and link previously buried data on a server. By leveraging these IoT technologies, it is possible to create more value and services than ever before. Increasing demand of outdoor IoT applications such as smart utilities and environmental monitoring, Low Power Wide Area Network (LPWAN) operating in the Sub-1 GHz (S1G) band is attracting attention. IEEE 802.15.4g [1], LoRa and SigFox based devices are already deployed in the market for these outdoor IoT application. Especially, IEEE 802.15.4g has been adopted as the communication standard for smart utility in Japan. In addition to forementioned wireless technologies in the S1G band, IEEE 802.11ah [2] is a new Wi-Fi standard marketed as Wi-Fi HaLow [3] and is expected to be utilized in various fields including smart home. Consumer devices around house such as intercom, security sensors and camera will be connected to Wi-Fi router using IEEE 802.11ah. These technologies have communication ranges up to 1000 meters. The use cases such as smart utility and smart home where many IoT devices are connected will increase, and IEEE 802.11ah and IEEE 802.15.4g based devices can be coexist. However, these two standards define different modulation schemes and frame structure, and very limited coexistence mechanism has been defined. Furthermore, the available frequency spectrum allocation for IEEE 802.11ah and IEEE 802.15.4g in the S1G band is limited to several MHz bandwidth in Japan. Even Japanese standard of ARIB STD-T108 [4] only allows up to 10 % transmission duty cycle to reduce traffic congestion, the interference mitigation can still become more difficult. Therefore, coexistence mechanisms between IEEE 802.11ah and IEEE 802.15.4g are very important.

This paper introduces the novel coexistence method to mitigate mutual interference between IEEE 802.11ah and IEEE 802.15.4g. The Reinforcement Learning based IEEE 802.11ah RAW scheduling is proposed to improve IEEE 802.15.4g performance.

The rest of this paper is organized as follows. Section 2 presents related work in the research community including our previous work. Section 3 introduces the coexistence behavior and issues. The proposed reinforcement learning based IEEE 802.11ah RAW scheduling is described in Section 4. Simulation results of our coexistence mechanism are presented in Section 5. Finally, we conclude our paper in Section 6.

2. Related Work

Research on IEEE 802.11ah and IEEE 802.15.4g has been conducted on various aspects. Table 1 shows the majority of performance evaluation and coexistence work.

For homogeneous networks, IEEE 802.11ah throughput evaluation has been demonstrated in [5] [6] [7] [8] using simulator. IEEE 802.11ah RAW has received attentions to support many IoT applications. [9] introduces the challenges for IoT applications and IEEE 802.11ah. Efficient ways of allocating STAs to RAW slots have been studied. [10] has proposed grouping STAs according to their backoff status. In [11], grouping of STAs according to traffic congestion has been studied. Similarly, IEEE 802.15.4g performance evaluation has been demonstrated in [12]

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Table 1 IEEE 802.11ah and IEEE 802.15.4g performance evaluation and coexistence work.

Reference	Year	Target System	Band	Objective	Validation Tool
A. Sljivo et al. [5]	2018	11ah	Sub-1 GHz	reliability, latency, throughput & energy	ns-3
A. Kureev et al. [6]	2017	11ah	Sub-1 GHz	energy & throughput	analytical & unknown sim.
L. Tian et al. [7]	2017/2016	11ah	Sub-1 GHz	throughput	ns-3
L. Tian et al. [8]	2016	11ah	Sub-1 GHz	throughput	ns-3
V. Boños-Gonzalez et al. [9]	2016	11ah	Sub-1 GHz	throughput	analytical
M. Qutab-ud din et al. [10]	2015	11ah	Sub-1 GHz	RAW scheduling	Omnet++
N. Ahmed et al. [11]	2020	11ah	Sub-1 GHz	RAW scheduling	analytical
C.S Sum et al. [12]	2013	15.4g	Sub-1 GHz	throughput	Qualnet, MATLAB
F. Righetti et al. [13]	2019	15.4g	Sub-1 GHz	packet delivery rate	experiments
R. Ma et al. [14]	2017	11b & 15.4	2.4 GHz	analytical model, throughput	analytical & unknown sim.
X. Zhang, et al. [15]	2011	11 & 15.4	2.4 GHz	analytical model, throughput	analytical, ns-2
J.Hou et al. [16]	2009	11 & 15.4	2.4 GHz	packet delivery rate	experiments
W. Yuan et al. [17]	2010	11b & 15.4	2.4 GHz	throughput	OPNET
J. Guo, P. Orlik [18]	2017	11ah & 15.4g	Sub-1 GHz	packet delivery rate and latency for coexistence	ns-3
Y. Liu, J. Guo et al. [19]	2018	11ah & 15.4g	Sub-1 GHz	packet delivery rate and latency for coexistence	ns-3
Y. Nagai, J. Guo et al. [20]	2020	11ah & 15.4g	Sub-1 GHz	packet delivery rate and latency for coexistence	ns-3
O. Carhacioglu, et al. [21]	2017	BLE & 15.4	2.4 GHz	packet error rate for coexistence	experiments

[13], which focus on the PHY and MAC protocol enhancement for higher-throughput, protocol efficiency and packet delay via simulation as well as measurement results using prototypes.

For coexistence of heterogeneous technologies, there are existing studies on the coexistence of conventional IEEE 802.11 network and IEEE 802.15.4 network. [14] investigates the coexistence issues of IEEE 802.11b network and IEEE 802.15.4 network in 2.4 GHz band. The system consists of an IEEE 802.15.4 transmitter, an IEEE 802.15.4 receiver and multiple IEEE 802.11b transmitters. The paper proposes a packet error rate (PER) based packet collision analytical model and a link quality indicator (LQI) based channel agility scheme for IEEE 802.15.4 network to perform channel re-selection for interference avoidance. It shows that IEEE 802.11b network can significantly interfere with IEEE 802.15.4 network. However, the paper treats IEEE 802.11b devices as interferer only without considering performance of IEEE 802.11b network. Some existing coexistence solutions require special devices. [15] designs a cooperative busy tone (CBT) to enable coexistence of IEEE 802.11 network and IEEE 802.15.4 network. CBT allows a separate IEEE 802.15.4 device to schedule a busy tone concurrently with the desired IEEE 802.15.4 transmission, thereby improving the visibility of IEEE 802.15.4 devices to IEEE 802.11 devices. However, calculation of the busy tone is based on Poisson data arrival with unsaturated traffic. Thus, the application of busy tone approach is limited since the coexistence issue is not severe when network offered load is light. [16] proposes a hybrid device implementing both IEEE 802.11 and IEEE 802.15.4 specifications so that it can transmit IEEE 802.11 and IEEE 802.15.4 messages. Therefore, this hybrid device can coordinate IEEE 802.11 and IEEE 802.15.4 networks and acts as a mediator between two heterogeneous networks. Even the hybrid device can signal long channel occupation to IEEE 802.11 devices, the approach is not practical due to the need of the hybrid device. In addition, collaboration between regular IEEE 802.15.4 devices and hybrid devices is difficult. [17] proposes a decentralized approach for IEEE 802.15.4 devices to mitigate interference by adaptively adjusting ED threshold in the presence of severe interference. The ED threshold is calculated based on the accumulated transmission failure. The approach can reduce the packet loss due to channel access failures and enhance the performance of IEEE 802.15.4g network. However, this approach cannot reduce the packet loss due to collision.

We have proposed a prediction based self-transmission control method to address coexistence of IEEE 802.11ah and IEEE 802.15.4g networks in S1G band [18], in which IEEE 802.11ah devices predicts the transmission time of upcoming IEEE 802.15.4g packet and suspend their transmissions to avoid interfering with upcoming IEEE 802.15.4g packet transmission. However, the prediction is not accurate when IEEE 802.15.4g packet generation is high. Accordingly, we have further addressed coexistence issues of IEEE 802.11ah network and IEEE 802.15.4g network in S1G band. Our learning based coexistence control techniques using machine learning approach added the intelligence into IEEE 802.11ah devices in [19]. We first present an $\alpha-$Fairness based energy detection clear channel assessment (ED-CCA) method that enables IEEE 802.15.4g packet transmissions. We then introduce a Q-Learning based backoff mechanisms for IEEE 802.11ah devices to avoid interfering with IEEE 802.15.4g packet transmission process. However, this approach causes big packet delivery rate (PDR) loss for IEEE 802.11ah network in order to improve IEEE 802.15.4g network PDR. We also proposed Hybrid CSMA/CA for IEEE 802.15.4g side to improve IEEE 802.15.4g reliability with more aggressive channel access to compete with IEEE 802.11ah channel access [20].

For more powerful coexistence approach of heterogeneous networks, time domain based coexistence approach is proposed for BLE and IEEE 802.15.4 in 2.4 GHz band [21]. Orchestrator connects both BLE central and IEEE 802.15.4 coordinator and meditates transmission timing for both systems. Beacon interval for IEEE 802.15.4 is divided into active period and inactive period to accommodate BLE. However, this approach requires orchestrator. To the best of our knowledge, no other existing work addresses IEEE 802.11ah network and IEEE 802.15.4g, or time-domain based heterogeneous network coexistence.

3. Coexistence behavior and issues

Coexistence of IEEE 802.11ah and IEEE 802.15.4g has been

Table 2 Packet Delivery Rate and Latency

Net. Offered Load [kbps]		Packet Delivery Rate [%]		Packet Latency Avg. [ms]	
802.11ah	802.15.4g	802.11ah	802.15.4g	802.11ah	802.15.4g
20	20	100	98.1	9.9	22.3
40	20	100	94.0	16.7	26.9
60	20	100	84.7	45.4	34.6
80	20	99.9	67.9	144.7	39.1
100	20	99.7	49.1	169.1	44.2
20	30	100	94.2	12.1	26.2
40	30	100	86.4	23.5	32.1
60	30	100	71.4	101.2	38.6
80	30	99.8	54.7	175.0	42.5
100	30	99.4	36.0	189.4	48.3

studied in IEEE 802.19.3 Task Group since 2018. IEEE 802.19.3 is focusing on developing a recommended practice standard that provides guidance on the implementation, configuration and commissioning of systems based on IEEE 802.11ah and IEEE 802.15.4 Smart Utility Networking (SUN) FSK PHY operating in the S1G frequency bands to achieve the best possible performance when sharing spectrum. Authors of this paper initiated task group formation and have been leading this task group.

Use case scenarios and simulation scenarios are defined in [23] to identify coexistence behavior and issues. We have developed a NS-3 based coexistence simulator for IEEE 802.11ah and IEEE 802.15.4g using third party IEEE 802.11ah module [8]. For coexistence simulation, additional interfaces and functions to calculate mutual interference have been implemented [22]. This simulator has been used in IEEE 802.19.3 Task Group. Table 2 shows coexistence simulation results using functions defined in IEEE 802.11ah and IEEE 802.15.4g. It can be seen that IEEE 802.15.4g PDR decreases significantly as IEEE 802.11ah offered load increases. Packet latency for both IEEE 802.11ah and IEEE 802.15.4g increases as the offered load increases because of retransmission. Details can be found in our presentations in IEEE 802.19.3 Task Group [24] [25]. These results indicate that further coexistence mechanism for IEEE 802.11ah and IEEE 802.15.4g is needed. Especially, it is necessary to improve IEEE 802.15.4g based smart utility applications including smart meter usage and demand response.

4. Reinforcement Learning based 802.11ah RAW scheduling

IEEE 802.11ah supports new uplink channel access scheme to a small number of STAs and spreading their uplink access attempts. Restricted Access Window (RAW) in IEEE 802.11ah divides a time frame into a sets of RAW slots and allows a particular group of STAs to contend for transmission during a given slot as shown in Figure 1. Thus, unassigned STAs can't transmit packets during unassigned RAW periods.

We have proposed α-Fairness based ED-CCA in [19]. In this method, IEEE 802.11ah detects the presence of IEEE 802.15.4g and inhibits its own transmission to ensure the communication time for the IEEE 802.15.4g side, thus improving the PDR of IEEE 802.15.4g network. However, our method has a drawback such that IEEE 802.11ah STAs excessively suppress the transmission because IEEE 802.11ah STAs are not synchronized to make time period for IEEE 802.15.4g transmissions. Therefore,

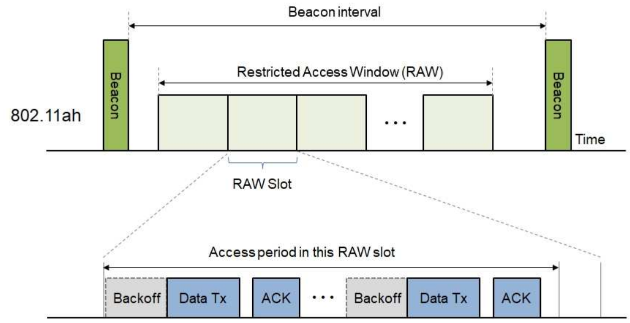

Fig. 1 IEEE 802.11ah RAW architecture

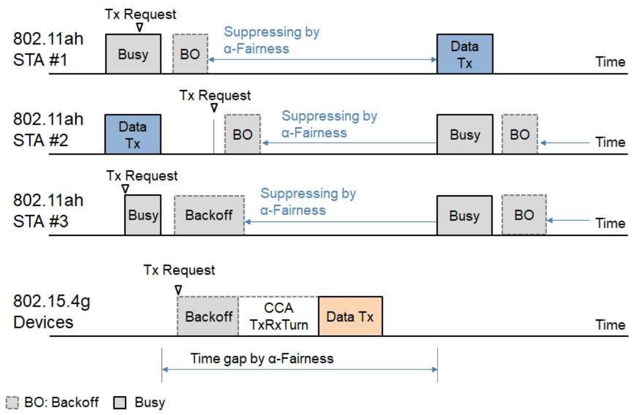

Fig. 2 Excessive suppression by α-Fairness based ED-CCA

as the number of devices increases, the transmission suppression period needs to be increased, and the PDR of IEEE 802.11ah network degrades significantly. Figure 2 shows that the idle period of IEEE 802.11ah STAs is very short relative to the time of bandwidth suppression. Furthermore, some information exchange between IEEE 802.11ah and IEEE 802.15.4g was required to estimate channel status.

In this paper, we propose a novel method to improve the performance of IEEE 802.15.4g and IEEE 802.11ah networks by combining IEEE 802.11ah RAW scheduling mechanism with Reinforcement Learning based CSMA/CA. We adopt Q-Learning as reinforcement learning.The proposed method does not require an orchestrator to mediate between heterogeneous radio systems such as [21] [19]. In the proposed method, the IEEE 802.11ah AP performs Q-Learning based on the information collected from the IEEE 802.11ah STAs and spontaneously allocates bandwidth for the IEEE 802.15.4g devices. Since IEEE 802.11ah AP can use RAW to synchronize the transmissions of the IEEE 802.11ah STAs in allocated RAW slot, thus our proposal improve bandwidth utilization efficiency by reducing useless transmission suppression for IEEE 802.11ah STAs.

Q-Learning is formulated as

$$Q_{t+1}(s,a) = (1-\tau_t)Q_t(s,a) + \tau_t(R_t(s,a) + \gamma V_t(s',b)),$$

$$V_t(s',b) = \max_{b \epsilon B(s')} Q_t(s',b), \tag{1}$$

where $Q_t(s,a)$ is Q-Learning objective function, s' is the state reached from state s by taking action a, $B(s')$ is action set that can be taken at state s', $0 < \tau_t < 1$ is the learning rate, $0 < \gamma < 1$

is the discount factor and $R_t(s, a)$ is the reward obtained by performing action a at state s at time t.State s shows the number of RAW slot, and action a shows the increasing or decreasing of number of slots.

To apply Q-Learning for wireless medium sharing, we can obtain the maximum value of the Q-Learning objective function as $V_t(s', b)$. The reward is defined as

$$R(s, a) = \frac{T_{15.4g}}{T_{11ahRAW}} + N \cdot PDR_{11ah} \quad (2)$$

where $T_{15.4g}$ is the estimated IEEE 802.15.4g transmission time observed by IEEE 802.11ah based on energy detection, $T_{11ahRAW}$ is current IEEE 802.11ah RAW time, PDR_{11ah} is observed Packet Delivery Rate for IEEE 802.11ah, and N is weighting factor. Figure 3 shows reinforcement learning based IEEE 802.11ah RAW scheduling for coexistence with IEEE 802.15.4g.

Based on reward design, if IEEE 802.11ah detects IEEE 802.15.4g severity, IEEE 802.11ah increases RAW slots for IEEE 802.15.4g transmission opportunity (increasing T_{idle}). On the other hand, if IEEE 802.11ah detects absence of IEEE 802.15.4g, IEEE 802.11ah decreases RAW slots for IEEE 802.15.4g transmission opportunity (decreasing T_{idle}).

5. Evaluation

In this section, we evaluate the proposed Reinforcement Learning based IEEE 802.11ah RAW scheduling performance compared with standard defined IEEE 802.11ah CSMA/CA. We adopt the simulation parameters and STAs/nodes deployment recommended by IEEE 802.19.3 Task Group [23]. All IEEE 802.11ah STAs and IEEE 802.15.4g nodes are deployed in a circle 200 meters in diameter area with density of 500 / km^2. 15 STAs/nodes for each of IEEE 802.11ah network and IEEE 802.15.4g network accommodated in the area. The frequency is in the 920 MHz band, transmission power is 13 dBm, 1 MHz channel for IEEE 802.11ah, 400 kHz channel for IEEE 802.15.4g, IEEE 802.11ah OFDM PHY rate is 300 kbps and IEEE 802.15.4g-FSK PHY rate is 100 kbps. Payload for both IEEE 802.11ah packet and IEEE 802.15.4g packet is 100 bytes. Network offered load, i.e., application data, is uniformly distributed among STAs/nodes so that IEEE 802.11ah STAs send packets to IEEE 802.11ah AP and IEEE 802.15.4g nodes send packets to IEEE 802.15.4g PANC (Personal Area Network Coordinator) in star network topology. SEAMCAT Extend Hata Model for propagation between terminals from below rooftop height to near street level is employed in the simulation. SEAMCAT Extended Hata Model (Suburban) is represented by a combination of NLOS and LOS. Standard defined parameters of IEEE 802.11ah and IEEE 802.15.4g are applied for beacon interval, RAW slot and so on. We also selected PDR and packet latency as performance metrics recommended by IEEE 802.19.3 Task Group.

Figure 4 shows PDR comparison for offered load of 80 kbps for IEEE 802.11ah network and 20 kbps for IEEE 802.15.4g network. It can be seen that the proposed method improves IEEE 802.15.4g PDR compared to conventional IEEE 802.11ah method using standard defined coexistence functions without significant degradation of IEEE 802.11ah PDR.

Table 3 shows a summary of various PDR and average latency results of IEEE 802.11ah network and IEEE 802.15.4g network by the proposed Reinforcement Learning based IEEE 802.11ah RAW scheduling. The corresponding results by the standard defined coexistence functions are shown in Table 2. Looking at the offered load $[11ah, 15.4g] = [80\,kbps, 20\,kbps]$ of saturated condition, the proposed Reinforcement Learning based IEEE 802.11ah RAW scheduling can improve IEEE 802.15.4g PDR by 7% without significant degrading IEEE 802.11ah PDR. For the offered load $[11ah, 15.4g] = [100\,kbps, 20\,kbps]$, our proposed method can achieved 20 % PDR improvement for IEEE 802.15.4g network in exchange for 12.4 % degradation of IEEE 802.11ah PDR. For packet latency, the proposed method slightly improves packet latency of IEEE 802.15.4g network under saturated condition. IEEE 802.11ah packet latency increases because of waiting time of RAW slots assigned to IEEE 802.15.4g network.

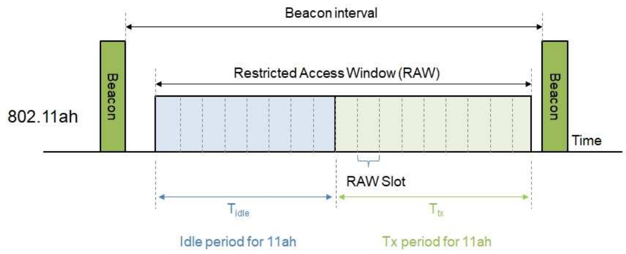

Fig. 3 Reinforcement Learning based 11ah RAW scheduling for coexistence with 15.4g

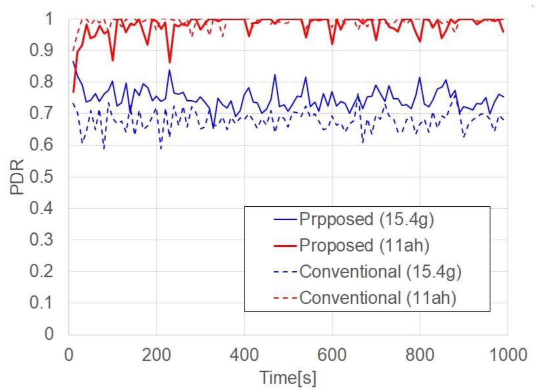

Fig. 4 Packet Delivery Rate Comparison for offered load of 80 kbps for IEEE 802.11ah and 20 kbps for IEEE 802.15.4g

Table 3 Packet Delivery Rate and Latency for proposed Reinforcement Learning based IEEE 802.11ah RAW scheduling

Net. Offered Load [kbps]		Packet Delivery Rate [%]		Packet Latency Avg. [ms]	
802.11ah	802.15.4g	802.11ah	802.15.4g	802.11ah	802.15.4g
20	20	100	98,0	9.9	22.2
40	20	100	93.8	16.9	27.1
60	20	99.8	85.4	199.5	33.2
80	20	99.2	74.9	234.3	36.6
100	20	87,3	69.1	234.7	37.7
20	30	100	94.4	12.0	26.2
40	30	100	86.5	23.4	32.0
60	30	99.7	73.8	240.3	37.4
80	30	97.6	60.8	151.8	40.2
100	30	81.5	57.9	252.5	40.9

6. Conclusion

With the increasing demand in outdoor IoT applications such as smart utilities, LPWAN operating in the Sub-1 GHz frequency band is attracting attention. IEEE 802.15.4g, LoRa and SigFox based devices are already deployed in the market. In addition, IEEE 802.11ah is promising for the smart house use cases with consumer devices and systems. Accordingly, the use cases such as smart utility and smart home will increase, and the coexistence of multiple wireless systems will become a challenge. We focus on use cases around house such as IEEE 802.15.4g based smart utility and IEEE 802.11ah based smart home. Simulation results with standard defined coexistence functions of IEEE 802.15.4g and IEEE 802.11ah, such as energy detection, show significant performance degradation for IEEE 802.15.4g network when IEEE 802.11ah network coexist in same area. We propose a novel method to reduce mutual interference between IEEE 802.15.4g network and IEEE 802.11ah network by applying reinforcement learning to the IEEE 802.11ah RAW scheduling. Results shows that compared to standard defined coexistence functions, our proposed method improves 7 % packet delivery rate of IEEE 802.15.4g network without degradation of IEEE 802.11ah network packet delivery rate. Furthermore, our proposed method can improve packet delivery rate of IEEE 802.15.4g network by more than 20 % in exchange for 12.4 % degradation in IEEE 802.11ah network packet delivery rate. From these results, we conclude that our proposed method can improve IEEE 802.15.4g performance compared to conventional IEEE 802.11ah coexistence mechanism. Performance evaluation of multi-hop IEEE 802.15.4g network and feasibility study using actual equipment will be addressed in the future works.

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