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Hybrid Traffic Scheduling in 5G and Time-Sensitive Networking Integrated Networks for Communications of Virtual Power Plants

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Abstract: The virtual power plant is one of the key technologies for the integration of various distributed energy resources into the power grid. To enable its smooth and reliable operation, the network infrastructure that connects the components for critical communications becomes a research challenge. Current communication networks based on the traditional Ethernet and long-term evolution cannot provide the required deterministic low latency or reliable communication services. This paper presents a three-layer virtual power plant communication architecture with 5G and time-sensitive networking integrated networks for both determinism and mobility. The service types and traffic requirements of the virtual power plant are analyzed and mapped between 5G and time-sensitive networking to guarantee their quality of service. This paper proposes a semi-persistent scheduling with reserved bandwidth sharing and a pre-emption mechanism for time-critical traffic to guarantee its bounded latency and reliability while improving the bandwidth utilization. The performance evaluation results show that the proposed mechanism effectively reduces the end-to-end delay for both time-triggered traffic and event-triggered traffic compared with the dynamic scheduling method. For event-triggered traffic, the proposed mechanism has comparable end-to-end delay performance to the static scheduling method. It largely improves the resource utilization compared to the static scheduling method when the network load becomes heavy. It achieves an optimum performance tradeoff between delay and resource utilization when the percentage of the reserved resource blocks is 30% in the simulation.

Keywords: virtual power plant; 5G; time-sensitive networking; semi-persistent scheduling

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1. Introduction

The smart grid, microgrid, and virtual power plant (VPP) are key technologies to efficiently utilize renewable energies in the power grid for energy sustainability and a reduction in carbon emission [1]. The distributed generation technologies with renewable energy provide the advantages of reliability, economy, and flexibility for power grid systems. Renewable energy resources are expected to contribute more than 40% of the total generated electricity by the year 2050 [2]. However, distributed renewable energy such as wind, solar, water, and hydropower exhibits the characteristics of unpredictability, heterogeneity, randomness, fluctuations, and intermittence [3]. How to efficiently utilize the distributed energy resources by VPP while keeping the stability of the new power grid systems is a great research challenge. To improve the control and scheduling performance of the new power grid systems, information, communication and networking technologies are of great importance [4,5].

The VPP integrates various distributed energy resources (DERs), such as distributed power generation, energy storage, controllable loads, and electric vehicles, to incorporate them into the grid as a single administrator [6,7]. It provides the power auxiliary service with numerous advantages and incentives for customers, prosumers, and operators [8]. The VPP is implemented based on a software and network for sending and optimizing the distributed energy resources remotely and automatically [9]. The VPP consists of a group of dispersed generator units, loads, and storage systems. It operates as a single power plant. The VPP control center platform coordinates the power flow, load, and generator storage.

The VPP consists of three component technologies [1]. They are generation technology, storage technology, and information and communication technology (ICT). The generation technology consists of stochastic natural energy sources (e.g., wind, water, and sunlight) and traditional dispatchable power plants and energy storage. The energy storage technology balances the energy production and supply according to the electricity demand change. The information and communication infrastructure connects the components of VPP and it enables efficient communication among them for the smooth and reliable operation of the VPP.

The current VPP communication technologies include Ethernet and LTE (long-term evolution) [10–12]. Ethernet and LTE are utilized for wireline and wireless communications between local DER systems and the remote VPP control platform. The dynamic operation of VPP requires low latency and a reliable communication service. For example, the fast frequency regulation dispatchable commands from the VPP control platform are expected to arrive at local DER system within tens of milliseconds without loss [11]. However, Ethernet frames may get lost due to network congestion and the delivery delay of Ethernet frames cannot be guaranteed [13]. The LTE technology provides flexible wireless access service but it lacks the capability for bounded low delay and a reliable communication service for critical traffic [14]. A hybrid wired and wireless deterministic network based on time-triggered Ethernet (TTE) and 5G for smart grids was proposed in [15]. However, the TTE protocols are private and the compatibility remains a problem to be solved. C. Feng et al. studied the device access optimization problem in heterogeneous networks of VPP considering the packet loss constraint [16], and this paper focuses on resource scheduling to guarantee packet delay. A decentralized IoT architecture of DER in VPP based on information pipe technology and cloud/fog computing was proposed in [17]. However, it is only for applications in DER management systems. The challenge in current network solutions for VPP is the packet delivery latency guarantee for critical delay-sensitive messages.

Time-sensitive networking (TSN) is a set of standards defined in the IEEE 802.1 working group to enhance the capabilities of Ethernet technology [18]. TSN has four enhancements compared with traditional Ethernet. The first part is traffic shaping and scheduling for the performance guarantee of bounded latency [19]. The second part is frame replication and elimination for reliability (FRER) [20,21]. The third part is high-precision time synchronization based on the generalized precision time protocol (gPTP) [22]. The fourth part is flexible network management and configuration based on the stream reservation protocol (SRP), centralized network configuration (CNC), and YANG (Yet Another Next Generation) data model [23]. The TSN is promising for applications in industrial automation systems, smart grids, in-vehicle communication networks, and so on. It guarantees the transmission performance of the critical traffic while providing a converged transport platform for other types of traffic at the same time.

TSN technology and its application in energy internet were presented in [24]. Research on TSN tests for smart substations was reported in [25,26]. The traffic mapping and delay analysis of GOOSE (Generic Object Oriented Substation Event) traffic in IEC61850 over TSN were studied in [27]. The time-aware shaping (TAS) mechanism of TSN was evaluated in substations compared with traditional Ethernet [28]. However, how to apply TSN to VPP has not been reported so far according to our knowledge.

The 3GPP 5G technology is also promising for applications in VPP. The 5G network provides three typical services: enhanced mobile broadband (eMBB), ultra-reliable and

ultra-low-latency communication (URLLC), and massive machine-type communication (mMTC). The research on the distributed energy scheduling method of VPP in 5G communication environments was reported [29]. Feng Cheng et al. proposed the application of 5G radio access network (RAN) slicing to assist the VPP in participating in frequency regulation services [30]. However, how to utilize the 5G technology for the transmission performance guarantee of time-critical traffic in VPP communications is still a research problem.

The 5G and TSN integrated networks are studied in 3GPP. The 5G system acts as a TSN bridge to connect TSN networks or TSN end systems. There is some reported research on 5G and TSN integrated network architecture [31,32], time synchronization [33,34], coordinated scheduling [35–37], network redundancy [38], and so on. However, to the best of our knowledge, there is no research on 5G and TSN integrated networks for VPP.

This paper presents a three-layer VPP communication architecture with 5G and TSN integrated networks. It proposes a semi-persistent scheduling with reserved bandwidth sharing and pre-emption (SPS-RBSP) for the time-critical traffic of VPP to guarantee bounded latency and reliability. Performance evaluation results show that the proposed SPS-RBSP effectively reduces the end-to-end delay for both time-triggered traffic and event-triggered traffic in VPP compared with the dynamic scheduling method. It improves the resource utilization compared to the static scheduling method when the network load increases.

The contributions of this work are as follows:

(1) We presented a three-layer VPP communication architecture with 5G and TSN integrated networks to provide a guaranteed bounded low-latency and reliable communication service.
(2) We analyzed the service types and traffic requirements of VPP and performed traffic mapping in 5G and TSN integrated networks to guarantee the consistency of QoS (quality of service).
(3) We designed a semi-persistent scheduling with reserved bandwidth sharing and pre-emption (SPS-RBSP) for the time-critical traffic of VPP and verified its advantages through extensive simulation results.

The rest of the paper is organized as follows: Section 2 presents the three-layer VPP communication architecture as well as the service types and traffic requirements of the VPP. Section 3 presents the 5G and TSN integrated network architecture for VPP communications. Section 4 explains the semi-persistent scheduling with reserved bandwidth sharing and pre-emption in 5G and TSN integrated networks for VPP. Performance evaluation and simulation results are shown in Section 5. Finally, the paper is concluded in Section 6.

2. Virtual Power Plant (VPP) Communication Architecture

2.1. VPP Communication Architecture

Information and communication technology (ICT) is indispensable for VPPs. The VPP communication architecture is divided into three layers based on their respective functions as shown in Figure 1. Its three layers include the VPP platform communication layer, the remote communication layer, and the local communication layer. The communication architecture enables the VPP to monitor the various DERs. From the perspective of the uplink direction, it provides real-time data transmissions of the collected device status to the VPP control platforms. A large quantity of energy storage, controllable loads, and electric vehicles are connected to the VPP control platforms through the communication architecture. From the perspective of the downlink direction, the instructions are generated by the VPP control platforms. For example, the power dispatching instructions and frequency regulation instructions are distributed to the corresponding VPPs and their aggregation control gateways through the communication architecture. The end devices perform the instructions to maintain the stability of the power grid system. The local communication layer enables the communications inside the VPP, while the remote communication layer connects the VPPs to the VPP control platforms. The three-layer VPP communication architecture divides the communication functions based on their different communication requirements. In addi-

tion, both wireline and wireless communications are considered in the design to provide heterogeneous access for various end devices.

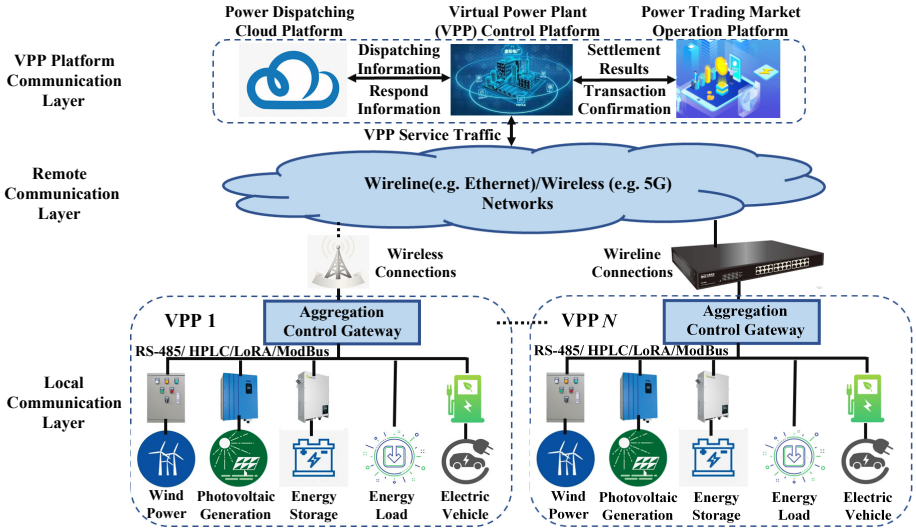


Figure 1. VPP communication architecture.

The VPP platforms include the VPP control platform, the power dispatching cloud platform, and the power trading market operation platform. They perform the functions of power control, power dispatching, and power trading, respectively. The power dispatching cloud platform communicates with the VPP control platform by exchanging the power dispatching information and responding information. The VPP control platform sends the power transaction confirmation information to the power trading market platform, while it provides the corresponding settlement information to the VPP control platform. The communications among them are named VPP platform communications. They are enabled by the remote wireline and wireless communication technologies. The three VPP platforms are considered as one large VPP control platform from the perspective of the various end devices.

The remote communication layer consists of wireline and wireless communication networks to connect the large VPP control platform and various end devices through VPP aggregation control gateways. Traditional remote communication technologies include Ethernet, optical networks, 4G LTE (long-term evolution), and dedicated wireless networks for power systems. Ethernet is a cost-effective communication solution thanks to its wide deployment and commercial maturity. But Ethernet cannot guarantee the packet delay and packet loss performance resulting from network congestion. Optical networks provide a large capacity and reliable data transmissions. However, they lack flexibility in network access and they increase the cost of network deployment. The dedicated wireless networks for power systems operate at the frequencies of 230 MHz and 1800 MHz. They are only deployed in some cities and they lack the performance guarantee in terms of delay and reliability. The 4G LTE has been deployed in almost all cities. It is suitable for status data collection in VPP systems. However, LTE technology has limited capabilities to guarantee the transmission of the critical data and the large volume of collected data at the same time.

The local communication layer connects the VPP aggregation control gateways with the various VPP end devices, such as various DERs (e.g., wind power and photovoltaic generation), energy storage, controllable loads, and electric vehicles. It enables communication among them inside the VPPs. The main components of local communication can be divided into three types. They are demand side resources, terminal equipment, and aggregation control devices. The demand side resources include DERs, various loads, and energy storage. The terminal equipment consists of smart meters, data collectors, and inverters. The aggregation control devices include telecontrol devices, concentrators, distribution automation terminals, and substation integration terminals. These end devices commu-

nicate with the aggregation control gateways through various communication protocols such as RS-485, Mod-bus, HPLC (high-speed power line communication), IP, and LoRA (Long-range RAdio). The aggregation control gateways are connected to the VPP control platforms through remote wireline or wireless communication networking. How to design the converged wireline and wireless remote network to guarantee the required performance of the critical traffic generated by the VPP systems is the main focus of this paper.

2.2. Service Types and Traffic Requirements of VPP

The communication service between the VPP control platforms and the end devices through the aggregation control gateways has various QoS requirements in terms of bandwidth, delay, and reliability. Table 1 shows the typical service types and traffic requirements of the VPP systems. We chose the frequency regulation, demand response, and power trade market as the typical service examples of VPP systems for further discussion.

Table 1. Typical service types and traffic requirements of VPP systems.

VPP Service	Bandwidth	Traffic Delay Requirements	Minimum Communication Delay Requirements	Target Delay	Reliability	Periodicity
Fast frequency regulation	4.8 Mbps (100 Terminals/km^2)	<280 ms	<120 ms	<50 ms	99.999%	Event-triggered
Regular frequency regulation	4.8 Mbps (100 Terminals/km^2)	<1 min	Seconds	<50 ms	99.99%	Event-triggered
Peak regulation	0.82 Mbps	<15 min	Minutes	<6 s	99.99%	Periodic (seconds) Time-triggered
Emergency demand response	16 Mbps (100 Terminals/km^2)	/	/	<50 ms	99.999%	Event-triggered
Normal demand response	2.74 Mbps (150 Terminals/km^2)	/	/	500–1100 ms	99.999%	Periodic (minutes) Time-triggered
Power trade market	1.33 Mbps (1000 trade members)	/	/	<10 s	99.99%	None

- Frequency regulation. The VPP provides the frequency regulation service through the control of DERs. Energy storage is one important unit for frequency regulation in VPPs. The participation of frequency regulation in VPPs presents great challenges to current communication networks. The delay requirement of fast frequency regulation traffic is less than 280 ms, with a communication delay requirement of less than 120 ms. The delay requirement of regular frequency regulation traffic is less than 1 min, with a minimum communication delay requirement of seconds. Its target delay is less than 50 ms and the required reliability is higher than 99.999%. The frequency regulation events trigger the time-critical communication in VPPs.
- Demand response. Demand response traffic is generated periodically. The normal demand response is time-triggered communication with cycles in minutes. The delay requirements of this type of traffic ranges from 500 to 1000 ms. The reliability requirement is as high as 99.999%. The emergency demand response is event-triggered communication. It has much lower delay requirements compared with the normal demand response.
- Power trade market. The transmission of power trade market information has a normal QoS requirement with delay of 10 s and reliability of 99.99%.

3. 5G and TSN Integrated Networks for VPP

The 5G and TSN integrated network is a promising communication solution for VPP as it provides an end-to-end deterministic communication service for time-critical traffic such as frequency regulation instructions and peak regulation instructions. The key features and advantages of the proposed 5G and TSN integrated network for VPP include

(1) 5G and TSN provide both a wireline and wireless communication service for end devices.
(2) 5G and TSN provide an end-to-end deterministic transmission service with bounded latency for time-sensitive VPP traffic.
(3) 5G and TSN provide a reliable communication service through redundancy technologies.
(4) 5G and TSN are standardized with good compatibilities.

As shown in Figure 2, the aggregation control gateways with dual connection modes can connect to 5G RANs (radio access networks) or TSN switches, respectively. The various local communication protocols and applications present great challenges to the aggregation control gateways. They connect to 5G RAN as a 5G UE. The traffic generated at the local communication networks to the aggregation control gateways is transported over the 5G network, including the 5G RAN, the 5G transport network, and the 5G core network, and finally to the VPP control platform. The aggregation control gateway can also connect to the TSN switch by wireline communications. TSN has a set of tools to guarantee the communication quality of various types of traffic from the local communication networks. TSN switches can be connected together to serve as the transport network for 5G as the fronthaul traffic has stringent delay and synchronization requirements. The VPP control platform sends instructions, such as dispatching instructions and frequency regulation instructions, to local end devices through the 5G and TSN integrated networks. How to guarantee the performance of the critical traffic in 5G and TSN integrated networks is a research problem.

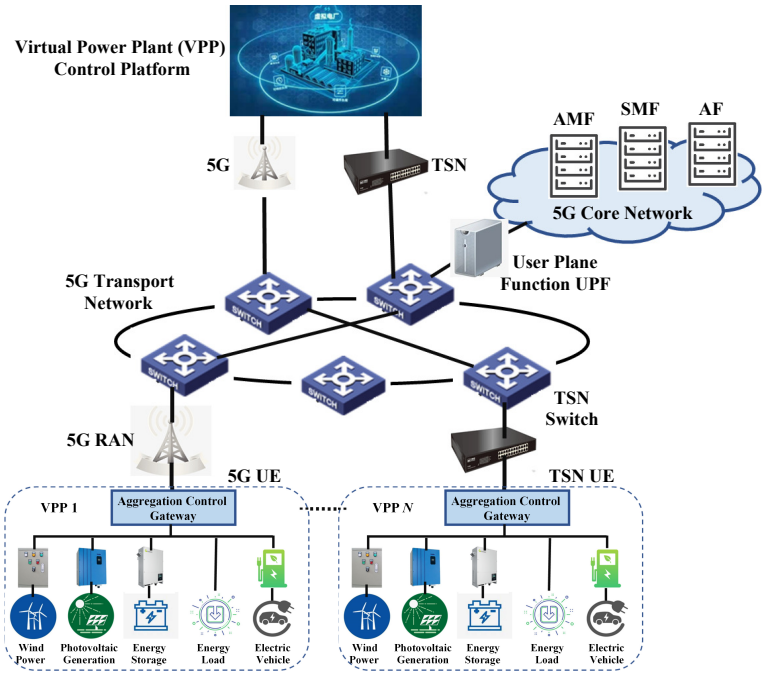


Figure 2. 5G and TSN integrated networks for VPP.

The 5G and TSN integrated networks are studied in their standardization organizations, such as 3GPP and IEEE. The 5G system could be considered as a transparent TSN switch for connecting different TSN networks through TSN translators. TSN could be used as the transport network for connecting 5G RAN and 5G core networks. The 5G and TSN integrated networks provide end-to-end deterministic transmission services for critical traffic in VPPs. The 5G networks provide flexible wireless access for end devices, while the TSN networks provide deterministic wireline access for end devices. However, the integration of 5G and TSN networks presents some research challenges, such as time synchronization, coordinated scheduling, and seamless reliability. More research on and standardization of 5G and TSN integrated networks are needed for future practical deployments in VPP.

4. Semi-Persistent Scheduling with Reserved Bandwidth Sharing and Pre-Emption (SPS-RBSP) for 5G-TSN VPP

4.1. QoS Mapping between TSN and 5G of VPP Traffic

The primary problem of VPP traffic transmissions in the 5G and TSN integrated network is performing the mapping of VPP traffic between the TSN and the 5G networks. Since different QoS frameworks are used in 5G and TSN networks separately, a reasonable QoS mapping rule needs to be designed in the coordinated scheduling process. The QoS mapping rule is utilized to map VPP traffic to TSN traffic classes and 5G QoS identifiers (5QI). To guarantee the delay and reliability of VPP traffic, correct and appropriate mapping is indispensable.

In the 5G and TSN integrated network, the 5G network communicates with the TSN centralized network configuration (CNC) in the control plane through the TSN application function (AF) module. TSN AF completes the mapping and interworking of the network configuration and management information. AF not only has a bridging capability, but it also converts the scheduling provided by the CNC to the 5G system. AF identifies the MAC address of the device-side TSN translator (DS-TT) of the corresponding protocol data unit (PDU) session, and it obtains the relevant TSN characteristic parameters of VPP traffic. After AF receives the TSN characteristic parameter information, it sends the information to the 5G policy control function (PCF). The PCF is responsible for mapping these TSN characteristic parameters to the 5G QoS parameters, generating a 5QI mapping table and sending it to the session management function (SMF). Then, the SMF configures the QoS parameters. On the user plane, VPP traffic is converted into the corresponding 5G QoS flow through the TSN translator. It configures the forwarding mechanism according to the mapping rules provided by the PCF.

In 5G networks, the SMF is responsible for controlling the QoS. When establishing a PDU session, the SMF configures the corresponding QoS parameters for the radio access network (RAN), including QoS configuration information such as 5QI and ARP (assign and retain priority). The 5QI value is standardized, including QoS characteristics such as packet delay budget, resource type, and priority. Priority indicates the criticality of the scheduling of the QoS flow. In 5G networks, different flows are identified through their 5QIs.

This paper adopts a static mapping strategy based on the traffic characteristics (priority, delay, reliability, etc.) of VPP traffic. Various types of VPP traffic are mapped to corresponding TSN traffic classes and 5QIs. In the 5G network, the 3GPP standardized 5QI to QoS feature mapping table [39] is referred to for the mapping procedure. In the 5QI standardized QoS feature mapping table, resource types are divided into delay-critical guaranteed bit rate (GBR), GBR, and non-GBR types. The GBR type is applicable to the traffic with high real-time requirements, and it can guarantee the bandwidth of the PDU session. Fast frequency regulation traffic, regular frequency regulation traffic, emergency demand response traffic, and normal demand response traffic have low delay (millisecond level) and bandwidth requirements, so they need to be mapped to the GBR type. Among them, fast frequency regulation traffic, regular frequency regulation traffic, and emergency demand response traffic have the lowest delay and the highest reliability requirements, which are mapped to the delay-critical GBR. The delay in the peak regulation traffic and power trade market traffic is of seconds, and they have low bandwidth and reliability requirements. They use the non-GBR resource type for transmissions. The non-GBR resource type is used for services with low real-time requirements. It needs to bear the requirement of reducing the rate in case of network congestion. A static mapping table based on traffic characteristics is shown in Table 2.

4.2. Semi-Persistent Scheduling with Reserved Bandwidth Sharing and Pre-Emption

The frames in the TSN and 5G integrated networks are forwarded independently according to the QoS framework of their specific technologies. However, considering the time criticality of VPP applications, it is recommended to jointly schedule traffic flows in both 5G and TSN. This section proposes a semi-persistent scheduling with reserved

bandwidth sharing and pre-emption (SPS-RBSP) mechanism. It reduces the transmission delay of VPP traffic, especially the event-triggered (ET) traffic, in the 5G and TSN integrated network. In the 5G system, the stream configuration is transmitted in the form of a QoS profile that includes QoS parameters such as 5QI. The SMF determines the appropriate resource allocation for QoS flows according to the QoS profile. The TSN can be used as a 5G transmission network to provide deterministic low-latency communication services for traffic through the gate control list (GCL).

Table 2. VPP service traffic and corresponding TSN priority and 5QI.

VPP Service	Bandwidth	Target Delay	Reliability	Priority in TSN	5QI (Priority)
Fast frequency regulation	4.8 Mbps (100 Terminals/km^2)	<50 ms	99.999%	7	82 (19)
Regular frequency regulation	4.8 Mbps (100 Terminals/km^2)	<50 ms	99.99%	6	82 (22)
Peak regulation	0.82 Mbps	<6 s	99.99%	5	6 (23)
Emergency demand response	16 Mbps (100 Terminals/km^2)	<50 ms	99.999%	4	84 (24)
Normal demand response	2.74 Mbps (150 Terminals/km^2)	500–1100 ms	99.999%	3	76 (56)
Power trade market	1.33 Mbps (1000 trade members)	<10 s	99.99%	0	8 (80)

4.2.1. Network Model

The 5G system provides scheduling for different QoS flows. Each QoS flow has a QoS flow ID (QFI), which can be configured in the same way as 5QI. The scheduler implements the same forwarding strategy for QoS flows with the same QFI. Therefore, different types of VPP traffic are assigned different 5QI values to perform different scheduling strategies. When VPP traffic reaches the 5G network, it is mapped to the QoS flow of the corresponding PDU session together with the corresponding QoS profile. For this, a set of flows $\boldsymbol{F}$ is defined in the network. Each flow $f \in \boldsymbol{F}$ is defined by its cycle time T, data size B, and delay requirement D, that is, $f =< T, B, D >$. For ET flows, the cycle time refers to the minimum interval between events, expressed as T^{event}. The cycle time of time-triggered (TT) flow is its period, expressed as T^{time}.

In 5G networks, time-frequency resources are quantified as resource blocks (RBs). An RB contains 12 subcarriers in the frequency domain and a transmission time interval (TTI) in the time domain. A TTI has 14 OFDM symbols by default, which is the minimum time unit for scheduling. R represents the total available transmission resources in the 5G network, R^S represents the number of resources reserved for traffic, and the remaining resources $R - R^S$ are used for dynamic allocation when traffic arrives.

4.2.2. Semi-Persistent Scheduling with Reserved Bandwidth Sharing and Pre-Emption Mechanism

In traditional networks, TT flows typically have higher priorities and stricter delay limits than ET flows. However, in VPP systems, ET flows have higher priority and more strict delay requirements than TT flows. Due to the special characteristics of VPP traffic, this section designs a scheduling mechanism based on semi-persistent scheduling with reserved bandwidth sharing and pre-emption (SPS-RBSP). The traditional dynamic access process of the 5G system is complex and it cannot guarantee to meet strict delay requirements. By reserving resources for traffic in advance, the access delay of traffic in the 5G system can be significantly reduced. Reserving resources can also ensure that time-critical traffic is not disturbed by other traffic. It ensures the reliability of time-critical traffic. The traffic in the VPP system can be divided into three categories: (1) ET flow, triggered by events, has the highest priority and target delay requirement (50 ms), including three types of traffic: fast frequency regulation, regular frequency regulation, and emergency demand response; (2) TT flow, with periodic arrival, has lower delay requirements, including peak regulation and normal demand response traffic; and (3) best effort (BE) flow has the lowest priority and delay requirements (second level), including power trade market traffic. Because the arrival times of ET flows are unpredictable, it will cause a serious waste of resources if it only reserves resources for ET flows.

Considering the highest priority and event-triggered characteristics of ET flows, in each semi-persistent scheduling period T_S, a set of fixed numbers of RBs are reserved for possible ET flows. The reserved RBs are sufficient for ET flows. Because the period of TT flows in the VPP system is very long and the delay requirement is low, the setting of the SPS period is based on the minimum event interval of the ET flow T^{event}, i.e., $T_S = T^{event}$. The minimum event interval of ET flows is generally equal to their delay requirement. In the SPS-RBSP, this set of fixed reserved RBs can be shared with TT flows when there are no arriving ET flows. It improves the resource utilization when the event interval of ET flows is long. The transmission period of TT flows T^{time} in the VPP system is in the order of seconds or minutes, which is several times T^{event}, that is, $T^{time} = nT^{event}$. In shared scheduling, the transmission order of frames is determined based on the delay requirement of traffic. Regardless of whether there is traffic occupying resources at present, high-priority ET flows will immediately obtain transmission resources when they arrive. This ensures the low latency and reliable transmission of time-critical ET flows. TT flows can be transmitted using idle reserved RBs when they arrive. If the reserved RBs are insufficient, the remaining TT flows and BE flows are orderly carried by by dynamic RBs through the dynamic access process.

Figure 3 shows the basic principle of the proposed SPS-RBSP mechanism. Each square represents one RB. Regardless of the actual bandwidth requirements for each type of traffic, the frequency of one RB is used in Figure 3 to represent the bandwidth of the traffic. Assume that the data size for each transmission of the ET flow is 1 RB, and the data size for each transmission of the TT flow is 4 RBs. Assuming $T^{event} = T_S = 50$ ms and $T^{time} = 1$ s, then $T^{time} = 20T^{event}$. As shown in case (a) of Figure 3, ET traffic may arrive at any time within T^{event}. Since T^{event} represents the minimum interval between events, it is also possible to pass several T^{event} before the next ET flow arrives. The TT traffic arrives at a fixed time in T^{time}. This is assumed every time the TT flow arrives at the second TTI.

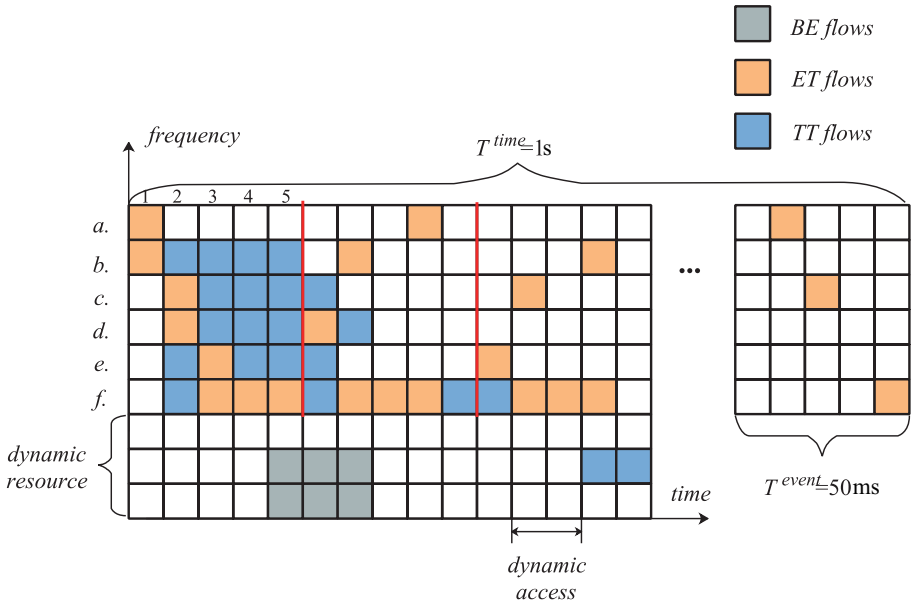


Figure 3. Reserved bandwidth sharing and pre-emption diagram.

In one SPS period, if the ET flow arrives before the TT flow, the TT flow can directly use the idle reserved resources for transmission when it arrives, as shown in case (b) of Figure 3. If the ET flow and the TT flow arrive at the same time, the ET flow will be transmitted first, and the TT flow will be transmitted after the ET flow transmission is completed, as shown in case (c) of Figure 3. When the TT flow is delayed to the next T^{event}, if another ET flow happens to arrive at this time, the TT flow will continue to be delayed, as shown in case (d) of Figure 3. If the event occurs after the transmission of the TT flow starts, when the ET flow arrives, the transmission of the TT flow frame will be interrupted and the resources

will be pre-empted. The remaining frames of the TT flow will continue to be transmitted after the transmission of the ET flow is completed, as shown in case (e) of Figure 3.

In the worst case, TT flows may require dynamic scheduling, as shown in case (f) of Figure 3. Assume that the data size of the ET flow is 3 RBs and the data size of the TT flow is 6 RBs. In this case, when events occur frequently, the possible idle reserved resources are not sufficient. The TT flow will be pre-empted multiple times and delayed for multiple T_S. When the delay of a TT flows approaches its deadline after multiple delays, dynamic resources are directly allocated to the TT flows. On the other hand, pre-empting a TT flow multiple times may increase its packet error rate. Therefore, when the possible idle reserved resources are less than the threshold, resources will be dynamically allocated to the flow. Since the delay requirement of TT flows in the VPP system is much larger than T_S, even if the TT flow is delayed to the next semi-persistent scheduling period, or dynamic scheduling is performed in the worst case, the target delay requirement of the TT flow can still be met.

4.2.3. Deadline-Aware Dynamic Resource Allocation in 5G

For TT flows with insufficient reserved resources and BE flows, dynamic scheduling is adopted. Dynamic scheduling determines the order of resource allocation based on the transmission priority and deadline of traffic. The scheduler is aware of the deadline of the current traffic while dynamically allocating resources. When the deadline is far away, the scheduler performs dynamic resource allocation based on the priority of traffic. If the traffic has a deadline requirement and the deadline is approaching, but no resources have been allocated for the traffic, the priority will be updated and resources will be allocated first, as shown in Equation (1).

$$f_i.deadline - f_i.t < \beta(f_j.deadline - f_j.t) \tag{1}$$

where $f.t$ represents the transmission delay of traffic and β is the time factor used to control the increased degree of priority.

In the SPS-RBSP algorithm, the optimization goal is to minimize the end-to-end delay of traffic, as shown in Equation (2).

$$\mathbf{P}: \quad \min \sum_{i=1}^{N} f_i.t^{E2E} \tag{2}$$

where N represents the number of flows in the network.

A. Time constraints

First of all, the frame scheduling time cannot be negative. For ET flows, the frame scheduling time ϕ should be after its occurrence time. The transmission of frames should conform to their periods.

$$TTflows: \quad f.\phi \geq 0 \tag{3}$$

$$ETflows: \quad f.\phi \geq f.st \tag{4}$$

$$f.\phi + f.t \leq T_S, \quad \forall f \in \boldsymbol{F} \tag{5}$$

Secondly, the scheduling time of the flow should meet its delay requirements:

$$f.\phi + f.t \leq f.D, \quad \forall f \in \boldsymbol{F} \tag{6}$$

where $f.\phi$ is the time when the frame of flow f starts scheduling. $f.st$ is only applicable to ET flows, indicating the occurrence time of the event. $f.t$ represents the transmission delay of traffic, including air interface delay t^{NR} and network transmission delay $t^{network}$.

B. Resource constraints

Each frame must be allocated a sufficient share of resources to transmit its entire frame at each scheduling time:

$$f.R^{\phi} \geq f.b^{\phi} \tag{7}$$

where R^{ϕ} represents the resources allocated for the frame and $^{\phi}$ indicates the data size of the frame.

C. TSN frame transmission constraints

When the TSN network is used as the 5G transmission network, VPP traffic needs to be transmitted through the TSN link. Each link of TSN can only be used by a single frame at the same time. Therefore, in order to ensure that any two frames from different flows will not interfere, they can only be scheduled when the other flow has completed its transmission:

$$(f_i.\phi + f_i.t^{network} \leq f_j.\phi) \vee (f_j.\phi + f_j.t^{network} \leq f_i.\phi), \quad \forall f_i, f_j \in \boldsymbol{F}, \quad f_i \neq f_j \tag{8}$$

D. Priority constraint

The priority determines the transmission queue and order of the flows. The priority transmission of high-priority traffic must be guaranteed during the scheduling process. In 5G networks, the higher-priority traffic is given a lower priority value. In TSN networks, the priority of traffic increases with its value:

$$\begin{cases} \text{5G}: & f_i.p \leq f_{i+1}.p \\ \text{TSN}: & f_i.p \geq f_{i+1}.p \end{cases} \tag{9}$$

To minimize the end-to-end transmission delay, a semi-persistent scheduling with reserved bandwidth sharing and pre-emption algorithm is shown in Algorithm 1. Firstly, partial resources are reserved for the ET flows based on their typical traffic characteristics. At the same time, reserved resources can be allocated to TT flows. When the ET flow arrives, if the reserved resources are not occupied, they will be directly allocated to the ET flow. If the reserved resources are occupied by the TT flow, the ET flow will pre-empt the resource and delay the transmission of the TT flow. When the reserved resources are exhausted, SPS-RBSP reassigns priority to the remaining traffic based on the deadline and performs dynamic resource allocation.

Algorithm 1 SPS-RBSP algorithm

Input: Traffic flows set $\boldsymbol{F}$, Total number of RBs R, SPS period T_S, The number of reserved RBs R^P

Output: The number of RBs allocated to flow f

Reserve resources R^P for ET flows
Perceived TT flows period and transmission
for all ET flows **do**
  if R^P is free **then**
    $f.ET$ transmission
  else if R^P is occupied by $f.TT$ **then**
    $f.ET$ pre-emption, $f.TT$ delay until $f.ET$ is transmitted
  end if
end for
for residual $f.TT$ and $f.BE$ **do**
  compute $f.t_{rem} = f.deadline - f.t$
  if $f_i.t_{rem} < \beta f_j.t_{rem}$ **then**
    $f_i.p++$
  end if
end for

5. Performance Evaluation and Simulation Results

5.1. Simulation Setup

The simulation parameters are shown in Table 3. In the simulation, it is assumed that the transmission delay of the 5G core network is 20 ms. The subcarrier spacing (SCS) of the 5G network is set as 15 kHz. The time slot length is set as 1ms. The number of OFDM symbols in one time slot is 14 by default. The time length of RB is one time slot, that is, 1 ms. Assuming that QAM64 modulation is adopted, the amount of data carried by one RB is 126 bytes. The semi-persistent scheduling period is set as the minimum event interval of the ET flows, i.e., T_S = 50 ms.

Table 3. Simulation parameters and values.

Parameter	Value
Delay of core networks	20 ms
Subcarrier spacing (SCS)	15 kHz
Modulation mode	64QAM
Transmission time interval (TTI)	1 ms
SPS period T_S	50 ms
RB carrying data volume	126 bytes

The simulation includes six types of traffic, including emergency demand response, fast frequency regulation, regular frequency regulation, normal demand response, peak regulation, and power trade market. The flow characteristic settings are based on Table 2. The number of reserved RBs is set based on the data size of three types of ET traffic, including fast frequency regulation, regular frequency regulation, and emergency demand response traffic.

In VPP systems, the delay guarantee of ET flows is critical. The 5G system uses limited spectrum resources to transmit data. The simulation compares the performance of the proposed SPS-RBSP algorithm with the traditional static scheduling algorithm and the traditional dynamic scheduling algorithm in terms of end-to-end delay and system resource utilization.

5.2. Simulation Results

Figure 4 shows the trend of system resource utilization with an increase in the network load. The proposed SPS-RBSP mechanism and dynamic scheduling mechanism achieve higher network resource utilization compared with static scheduling when there are more than 150 flows. When the number of scheduled traffic flows is more than 300 (i.e., under medium and high load), the resource utilization is higher than 80%. The traditional static scheduling algorithm reserves dedicated resources for ET flows with uncertain arrival times. However, other traffic cannot use these reserved RBs. It leads to a serious waste of resources when ET flows do not arrive for a long time, especially when the network load is heavy. The SPS-RBSP algorithm can share reserved resources with TT flows when reserved resources are idle, which greatly improves the resource utilization. In addition, dynamic scheduling for non-time-critical traffic improves the flexibility of resource allocation and increases the efficiency of resource utilization.

The proportion of reserved resources has a significant impact on the resource utilization efficiency of SPS-RBSP. Figure 4a–c show the resource utilization ratio when the reserved RB ratio is 20%, 30%, and 40%, respectively. When the percentage of reserved RBs is 40%, the resource utilization ratio of SPS-RBSP greatly decreases. This is because there are far more reserved RBs than the actual number of RBs required for ET and TT flows. However, the power trade market flows cannot use the unused reserved RBs, resulting in a waste of resources.

Figures 5 and 6 show the end-to-end delay performance comparison between the SPS-RBSP algorithm, the traditional static scheduling algorithm, and the traditional dynamic scheduling algorithm with different reserved RB ratios. The average end-to-end delays of

the event-triggered flows are shown in Figure 5. Compared with the dynamic scheduling algorithm, the SPS-RBSP algorithm and the static scheduling algorithm have smaller end-to-end delay, which can meet the target delay requirements (50 ms) of three high-priority ET flows (emergency response, fast frequency regulation, and regular frequency regulation) in VPP systems. This is because the SPS-RBSP algorithm avoids the complex SR-SG process by preallocating resource blocks for high-priority ET flows. It greatly reduces the access delay in 5G systems. The uncertain arrival time of ET flows makes it difficult to accurately predict the scheduling period. The SPS-RBSP algorithm ensures prioritized transmissions of time-critical ET flows through a pre-emptive scheduling mechanism. It further reduces the end-to-end delay of ET flows. At the same time, it reduces the overhead of control signaling and it has higher computational efficiency.

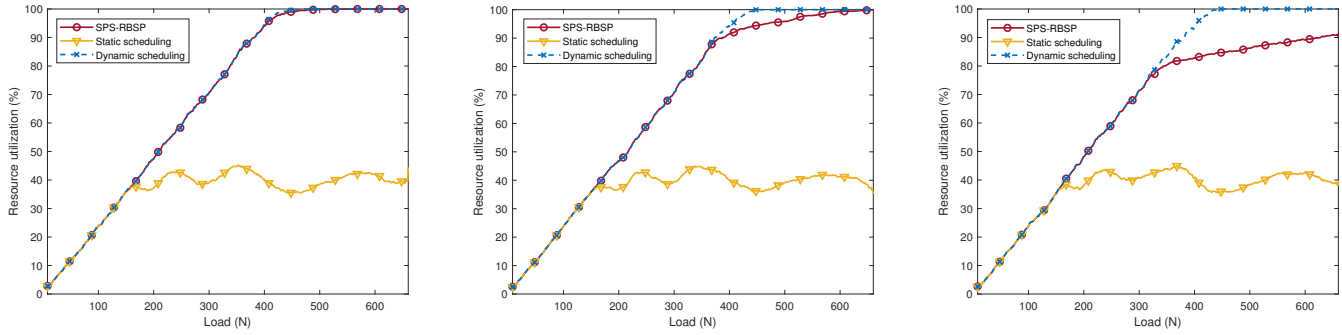


Figure 4. Comparisons of system resource utilization: (**a**) percentage of reserved RBs is 20%; (**b**) percentage of reserved RBs is 30%; (**c**) percentage of reserved RBs is 40%.

Additionally, it can be observed that when the percentages of reserved resources are 30% and 40%, SPS-RBSP has a similar delay to ET flows. When the percentage of reserved resources is 20%, the delay of SPS-RBSP is slightly higher, as shown in Figure 5a. This is because insufficient reserved RBs will lead to the queuing of ET flows, thereby increasing the end-to-end delay. Therefore, in order to achieve the deterministic low-latency scheduling of ET flows, it is necessary to reserve sufficient resources.

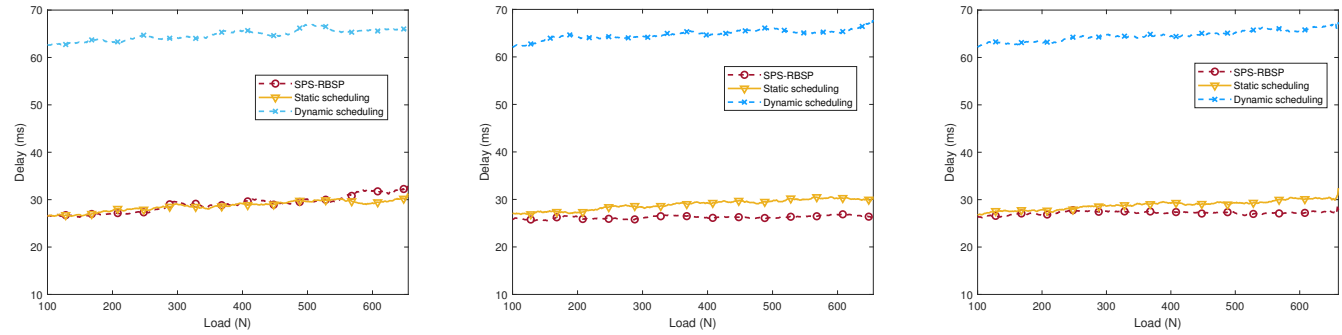


Figure 5. Comparisons of average end-to-end delay (event-triggered flows): (**a**) percentage of reserved RBs is 20%; (**b**) percentage of reserved RBs is 30%; (**c**) percentage of reserved RBs is 40%.

Figure 6 shows the average end-to-end delay of the periodic time-triggered flows. The end-to-end delay of the SPS-RBSP scheme is slightly greater than that of static scheduling. The reason is that a small part of the TT flows in the SPS-RBSP scheme may be allocated resources through dynamic access. However, due to the relaxed delay requirements of TT flows in the VPP system, the proposed SPS-RBSP scheme can still meet the transmission requirements of TT flows. The end-to-end delay of TT flows in the SPS-RBSP scheme is

much smaller than that in the dynamic scheduling scheme. The reason is that some TT flows in SPS-RBSP scheme can be carried by idle reserved resources to reduce the access delay of TT flows. As shown in Table 1, the delay requirement of TT flows in the VPP system is longer compared with that of ET flows. Although TT flows may be pre-empted and delayed by high-priority ET flows, they can still be transmitted within the latency bound in the SPS-RBSP. To sum up, under various traffic loads, the SPS-RBSP algorithm guarantees delay performance. It achieves low delay scheduling for different types of time-critical applications in VPP systems.

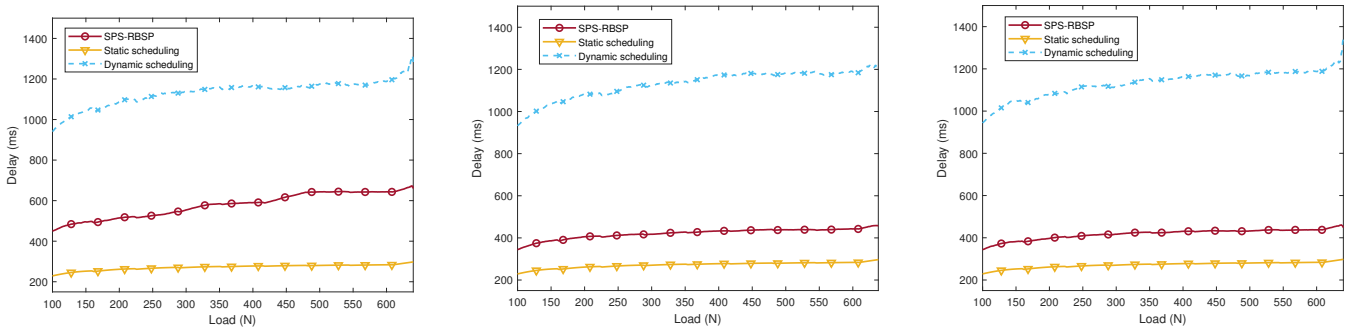


Figure 6. Comparisons of average end-to-end delay (time-triggered flows): (**a**) percentage of reserved RBs is 20%; (**b**) percentage of reserved RBs is 30%; (**c**) percentage of reserved RBs is 40%.

Comparing Figure 6a–c, when the percentage of reserved resources is only 20%, the delay of TT flows with the SPS-RBSP mechanism is much higher than that of the reserved RBs at 30% and 40%. This is because insufficient reserved RBs lead to there being no idle static resources to share with TT flows. As a result, the TT flows can only be dynamically scheduled, greatly increasing the access delay. Moreover, dynamic scheduling increases the possibility of conflicts between TT flows and other traffic. In addition, increasing the proportion of reserved RBs too much cannot significantly reduce the delay of TT flows. When the percentage of reserved RBs is 30%, SPS-RBSP has the lowest latency.

Figure 7 shows the performance tradeoff between the delay and resource utilization of SPS-RBSP under different percentages of the reserved RBs with 600 flows. The resource utilization sharply decreases when the percentage of the reserved RBs exceeds 30%. The delay of TT flows in VPP declines with the percentage of reserved RBs, and it becomes stable when the percentage is larger than 30%. The delay of ET flows in VPP is stable and it is always below 50 ms under different percentages of reserved RBs. This is because non-time-critical traffic cannot use the reserved RBs. More reserved RBs (>30%) for time-critical traffic may result in a waste of resource. The reservation of RBs can reduce the handshake delay in 5G systems. When the percentage of reserved resources is less than 30%, time-critical traffic cannot be completely carried by the reserved resources. If time-critical traffic is transmitted through the dynamic scheduling method, the access delay is increased. If time-critical traffic waits for reserved resources in the next cycle, the queuing delay is increased. It is suggested that the percentage of reserved RBs should be set as 30% to optimize the performance tradeoff between the delay and resource utilization of SPS-RBSP in the VPP under the simulation parameters.

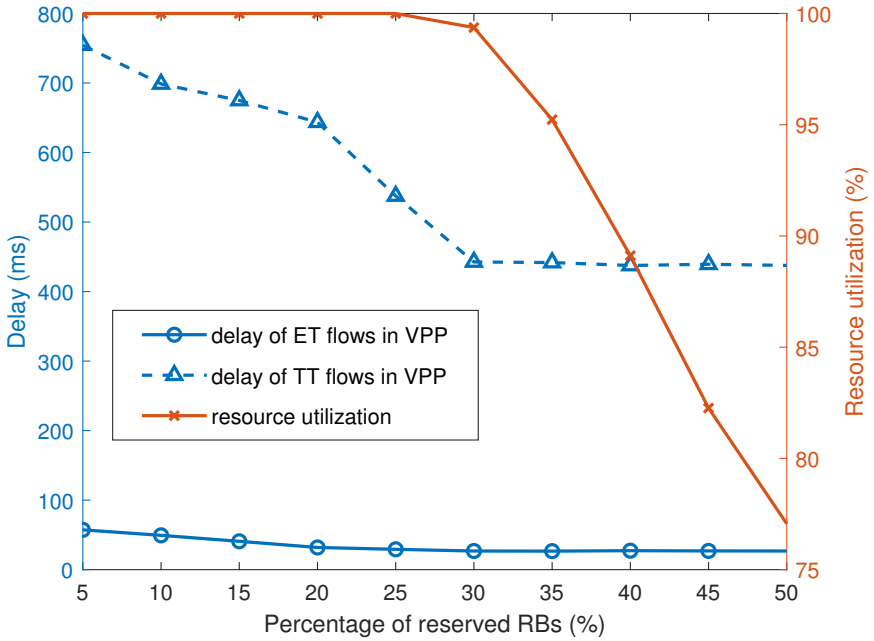


Figure 7. Performance tradeoff between delay and resource utilization of SPS-RBSP.

6. Conclusions

This paper presented a three-layer virtual power plant communication architecture with 5G and TSN integrated networks to provide a deterministic low latency and a reliable mobile communication service. The service types and traffic requirements of the virtual power plant were analyzed and mapped to 5G and TSN integrated networks to guarantee the consistency of QoS. It proposed semi-persistent scheduling with reserved bandwidth sharing and pre-emption in 5G and TSN integrated networks for both time-triggered and event-triggered critical traffic. The simulation results show that the proposed scheduling mechanism achieves much lower end-to-end latency for both event-triggered and time-triggered critical traffic flows compared with the dynamic scheduling method. It has comparable performance in terms of the system resource utilization compared with the dynamic scheduling method. It has better resource utilization efficiency than the static scheduling method when the network load becomes heavy. It achieves an optimum performance tradeoff between delay and resource utilization when the percentage of reserved resource blocks is 30% in the simulation.

Future research works include the design of a reliability mechanism and the time synchronization of 5G and TSN integrated networks for virtual power plant communications. Frame replication and elimination for a redundancy scheme of TSN and a dual connectivity scheme of 5G are expected to be converged for seamless reliability in 5G and TSN integrated networks. Time synchronization is also one of the key challenges in 5G and TSN integrated networks due to their different time-synchronization technologies. How to transparently perform time synchronization between different 5G and TSN domains requires further study. Both a reliability mechanism and time synchronization technology would improve the network performance in terms of determinism and reliability for virtual power plant applications. The presented 5G and TSN integrated communication network architecture and the proposed traffic scheduling mechanism can also be extended or modified for applications in other areas, such as industrial control automation systems.

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