Integration of Passive Optical Network and WiFi for F5G and Beyond

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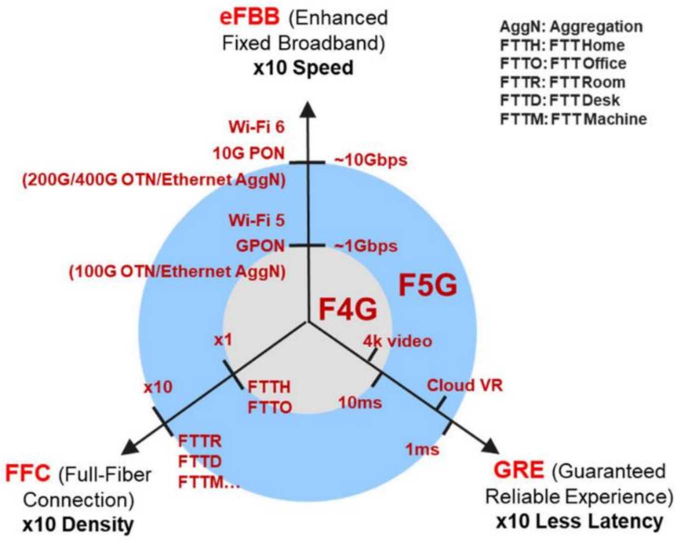
Soochow University

Outline

- **Background**
  - F5G requirements
  - WiFi technologies for F5G
  - PON technologies for F5G
- **Integration of OFDM-PON and WiFi**
  - Integration of OFDM-PON and WiFi
  - Water filling based resource allocation

Fifth generation fixed network

- Three key features of F5G, defined according to ETSI standards:
  - **Enhanced Fixed Broadband (eFBB):** Gigabit access capacity is to be achieved
  - **Full-Fiber Connection (FFC):** Service scenarios are expanded by 10 times, and the number of connections is increased by more than 100 times, enabling the era of full-fiber connectivity
  - **Guaranteed Reliable Experience (GRE):** almost-zero packet loss, microsecond-level delay and jitter are needed to meet users' requirements for the ultimate service experience



Technical characteristics of F5G

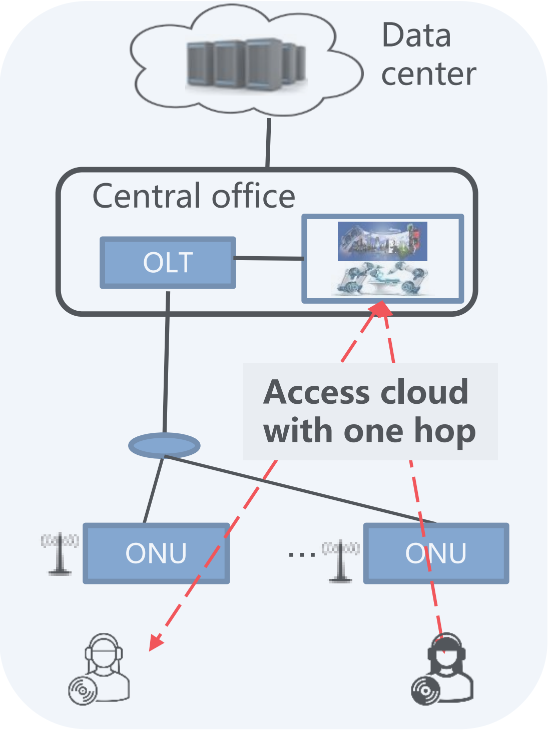
WiFi and PON are two key technologies to enable F5G

ETSI, "Fifth Generation Fixed Network (F5G)," Release 1, Dec. 2020.

Converged access network for F5G

- **Multiple service scenarios need to be supported： cloud VR, smart home, and online game…**
  - Stringent requirements on network **latency** and **capacity**
- **To satisfy the requirements of the above time-sensitive services**
  - Migrate these services to edge nodes (e.g., central office) that are closer to end users
  - PON and WiFi are coordinated to provide **one-hop access to cloud services** for end users

How to coordinate PON and WiFi to achieve a deterministic network performance?



OLT: Optical line terminal
ONU: Optical network unit

ETSI, “Fifth Generation Fixed Network (F5G),” Release 1, Dec. 2020.

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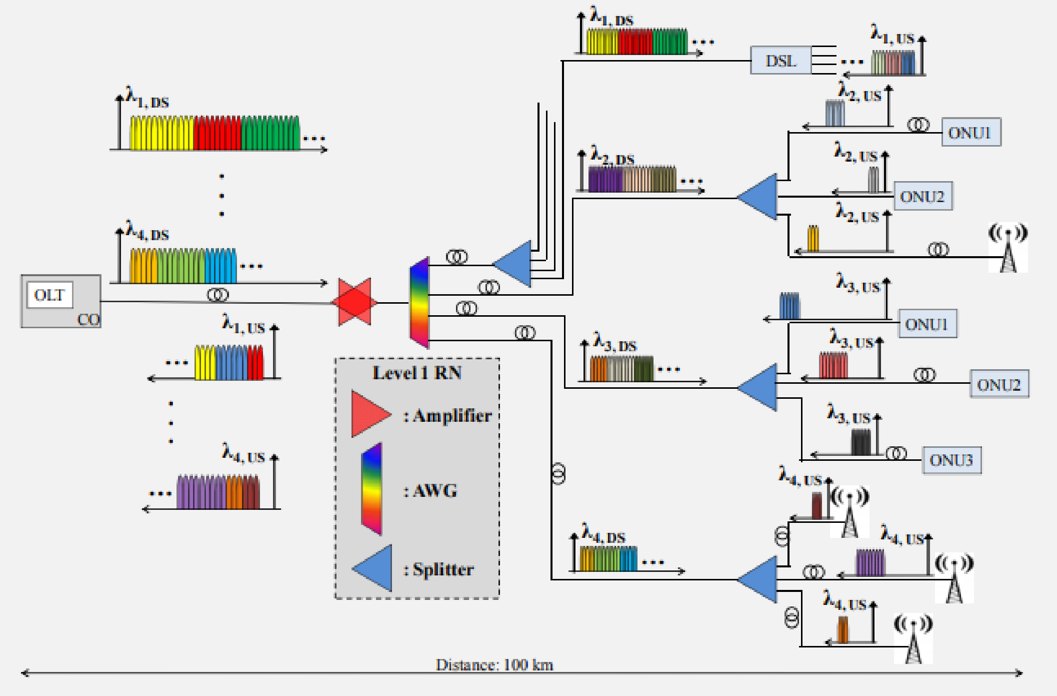
Evolution of WiFi technology

Protocol category	Time	Spectrum	Key parameters and techniques	
			PHY	MAC
802.11a	1999	5 GHz	Maximum data rate 54 Mb/s, OFDM	Basic channel access (CSMA/CA) Random channel access (DCF, EDCA) Contention-free channel access (PCF, HCCA) Static fragmentation (A-MSDU, A-MPDU)
802.11b	1999	2.4 GHz	Maximum data rate 11 Mb/s, DSSS	
802.11g	2003	2.4 GHz	Maximum data rate 54 Mb/s, 20 GHz, OFDM	
802.11n	2009	2.4 GHz, 5 GHz	Maximum data rate 600 Mb/s, 40 GHz, 4 antennas, MIMO	
802.11ac	2013	5 GHz	Maximum data rate 6.9 Gb/s, 160 GHz, 8 antennas, 256 QAM, downstream MU-MIMO	
802.11ax (WiFi 6)	2019	2.4 GHz, 5 GHz	Maximum data rate 9.6 Gb/s, 160 GHz, 8 antennas, 1024 QAM, downstream and upstream MU-MIMO	OFDMA, UORA, Trigger-based UL OFDMA, flexible fragmentation
802.11be (WiFi 7)	Next generation	2.4 GHz, 5 GHz, 6 GHz	Maximum data rate 40 Gb/s, 320 GHz, 16 antennas, 4096 QAM, downstream and upstream MU-MIMO	Enhanced OFDMA, multi-AP cooperation, multi-link operation, new access categories

E. Khorov, et al., "Current Status and Directions of IEEE 802.11be, the Future Wi-Fi 7," IEEE Access, April 2020.
E. Khorov, et al., "A Tutorial on IEEE 802.11ax High Efficiency WLANs," IEEE Communication Survey & Tutorials, vol. 21, no. 1, 2019.

OFDM-PON

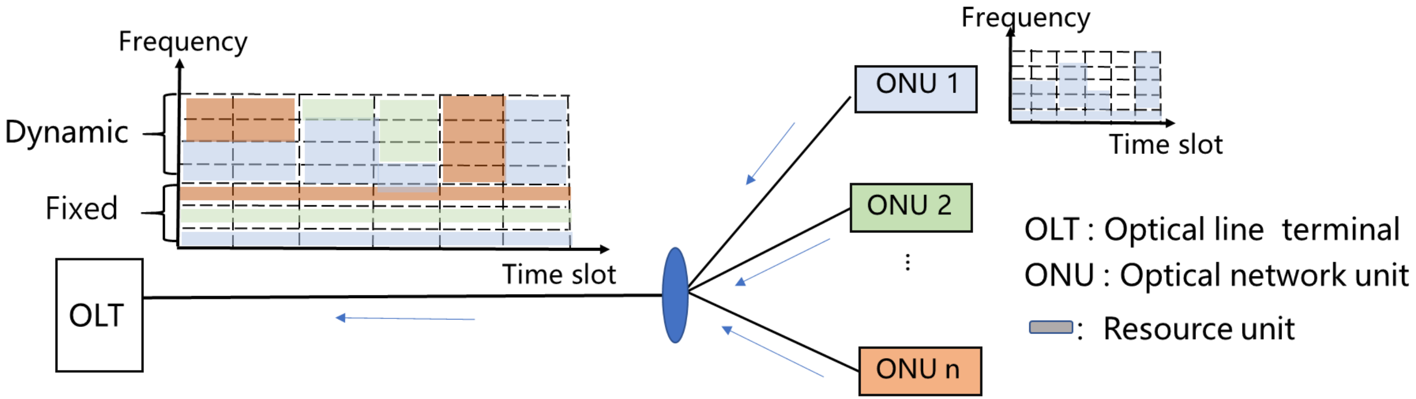
- Orthogonal frequency division multiplexing (OFDM) is a technology supporting multi-carrier transmission, based on which OFDM-PON enables multiple ONUs transmit data simultaneously



W. Lim, et al., "MAC Protocol Designs for OFDMA-PONs," IEEE ISCIT, 2014.

OFDM-PON

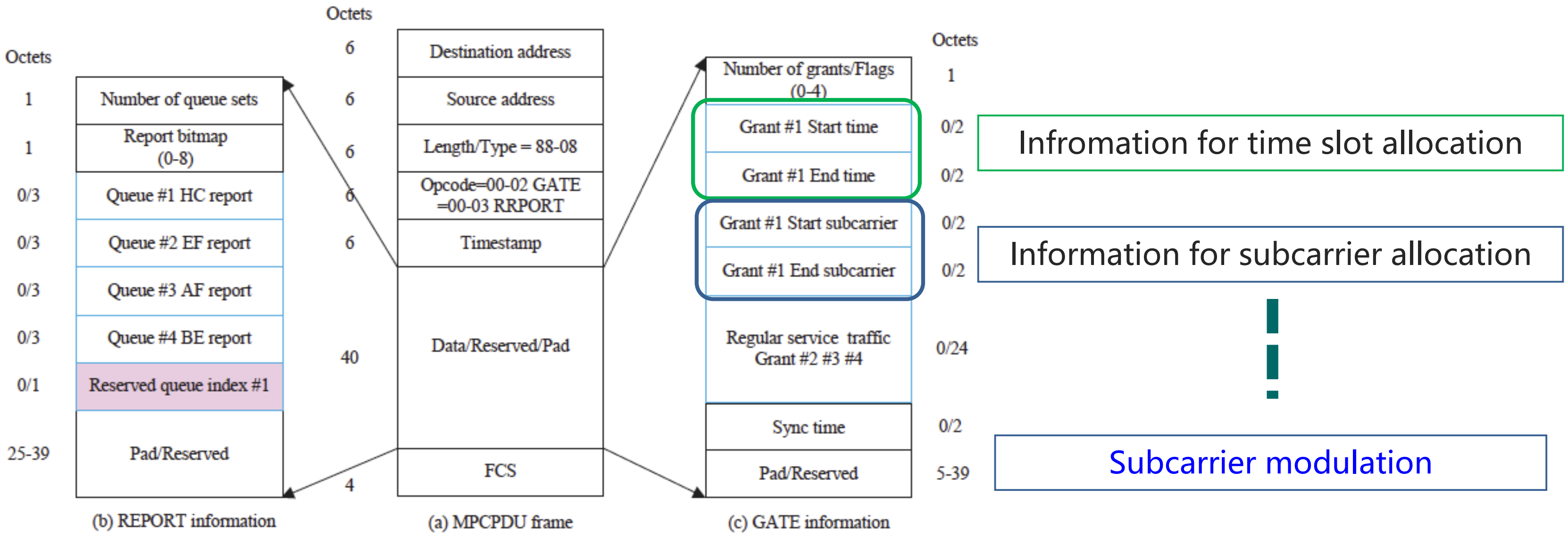
- ➢ Fixed bandwidth can be allocated to high-priority services
  - To meet a **stringent latency requirement**
- ➢ Bandwidth can be allocated dynamically to low-priority services
  - To improve **bandwidth utilization**



OFDM-PON is considered as one of the promising technologies to support real-time services

OFDM-PON MAC layer

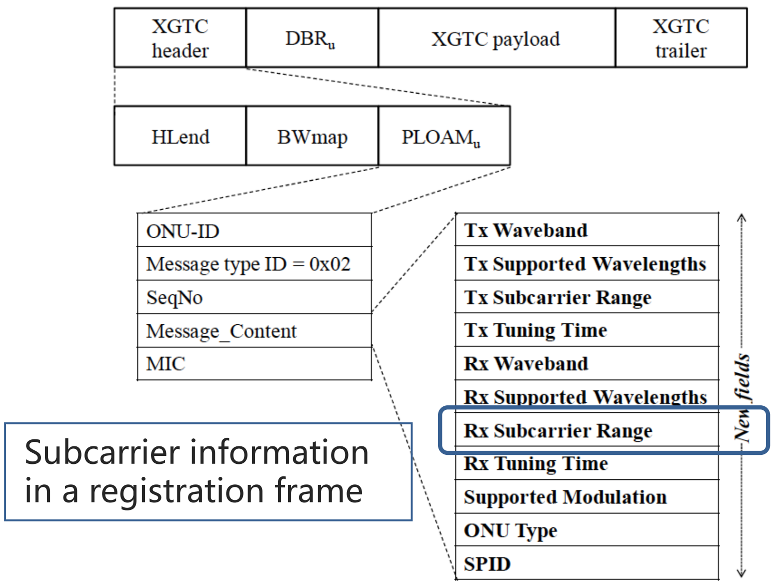
- In OFDM-PON, dynamic bandwidth allocation can be realized based on the existing protocols and frame formats of EPON and GPON
- EPON example: subcarrier information is added in the reserved bytes of an EPON frame



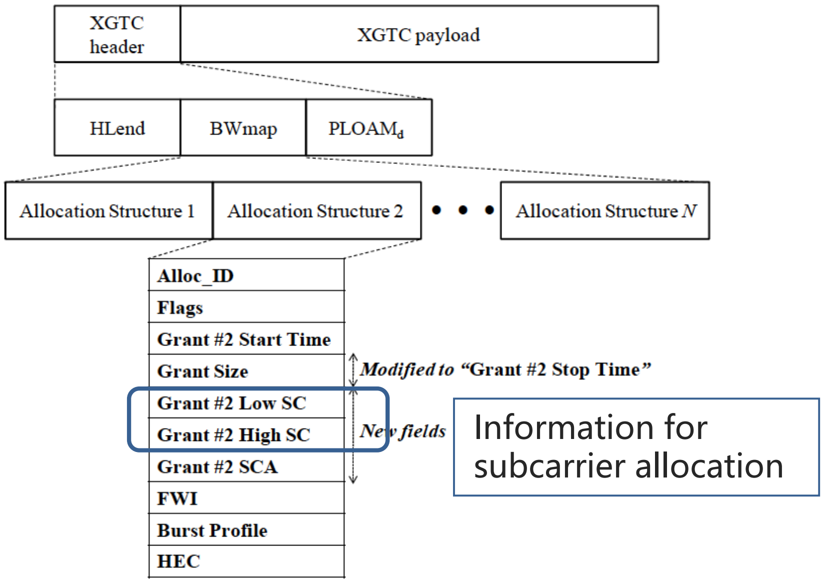
Y. Liu, et al., "Standard-Compliant Dynamic Bandwidth Allocation in OFDM-PON Supporting Multi-Service," in Asia Communications and Photonics Conference (ACP), 2018.

OFDM-PON MAC layer

- GPON example： subcarrier information is added in the reserved bytes of a GPON frame



(a) Modified REGISTER message in XG-PON US frames



(b) Modified US BW map in DS frames

W. Lim, et al.,"MAC Protocol Designs for OFDMA-PONs," IEEE ISCIT, 2014.

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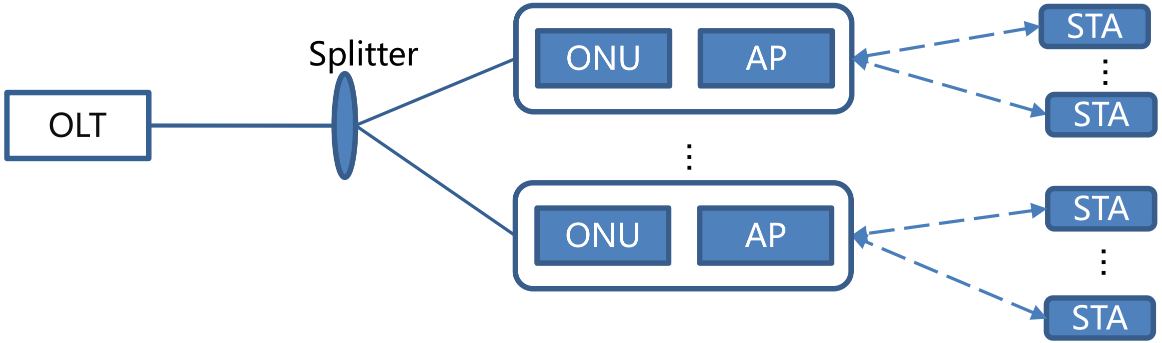
Converged access network: OFDM-PON and WiFi



OLT: Optical line terminal

ONU: Optical network unit

AP: Access point

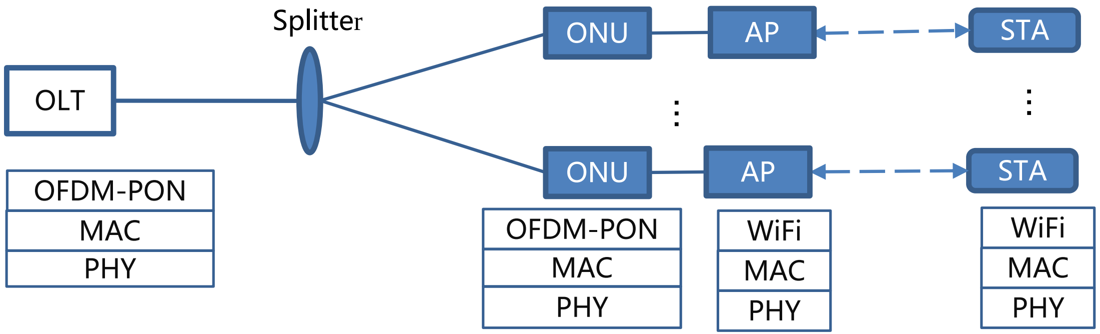
STA: Station

- STA can access AP via a wireless link， where AP is connected with ONU
- Three schemes for the integration of ONU and AP

- **Scheme 1**： AP and ONU are independent and connected via a standard communication interface
- **Scheme 2**： AP and ONU are integrated via MAC layer
- **Scheme 3**： AP and ONU are integrated via PHY layer

G. Shen, et al., "Fixed Mobile Convergence Architectures for Broadband Access: Integration of EPON and WiMAX," IEEE Communication Magazine, 2007.

Scheme 1: Independent architecture



OLT: Optical line terminal

ONU: Optical network unit

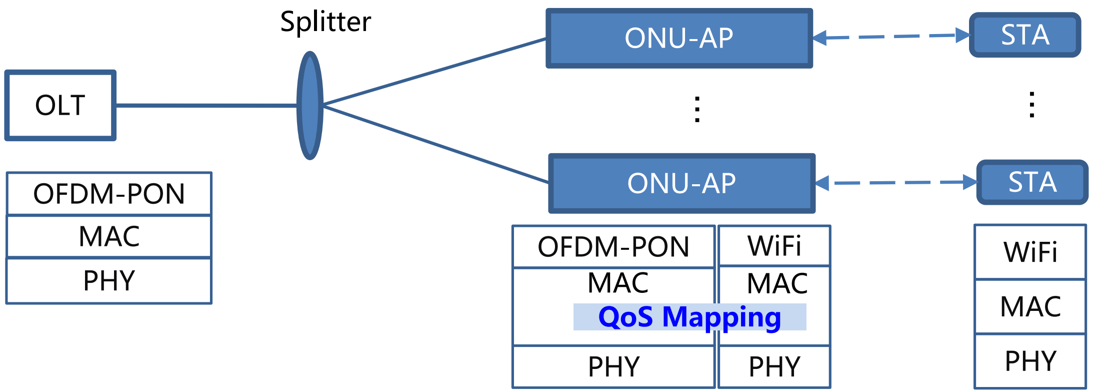
AP: Access point

STA: Station

➢ **AP and ONU are independent and connected via standard communication interface**

- **Advantage:** ONU and AP are connected without any extra adjustment and adaption
- **Disadvantage:** ONU and AP schedule their resources independently without joint optimization, and may increase scheduling delay and device cost

Scheme 2: MAC-layer integrated architecture



OLT: Optical line terminal

ONU: Optical network unit

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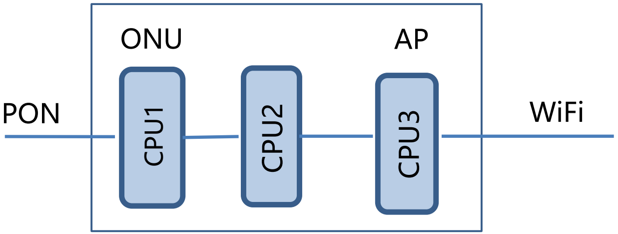
➢ AP and ONU are integrated in MAC layer

- **Advantage**: WiFi and PON exchange information to realize joint optimization for resource allocation, thus QoS can be improved and the cost of integrated devices can be reduced

Scheme 2: ONU-AP design

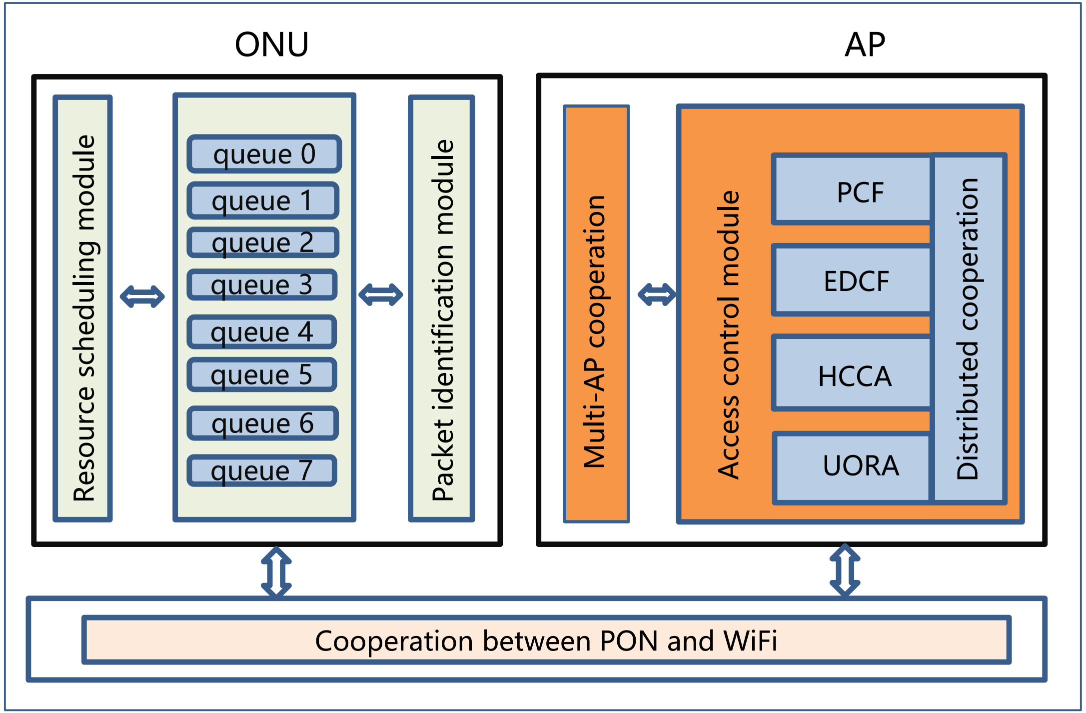
Diagram of hardware module



- CPU1 for PON protocol
- CPU2 for cooperation between PON and WiFi
- CPU3 for WiFi protocol

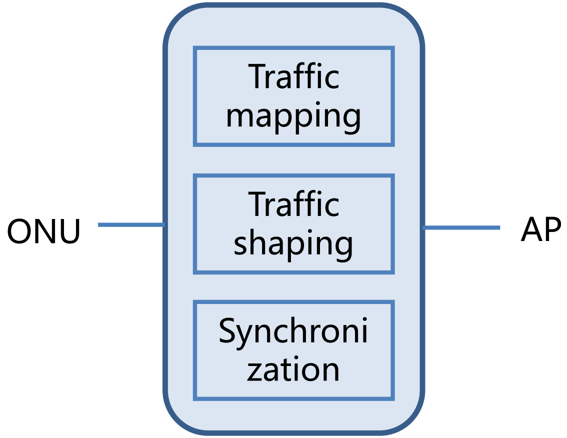
> ➢ A cooperation function is added, which avoids the modification of PON and WiFi protocols

Diagram of function module



G. Shen, et al., "Fixed Mobile Convergence Architectures for Broadband Access: Integration of EPON and WiMAX," IEEE Communication Magazine, 2007.

Scheme 2: PON and WiFi cooperation



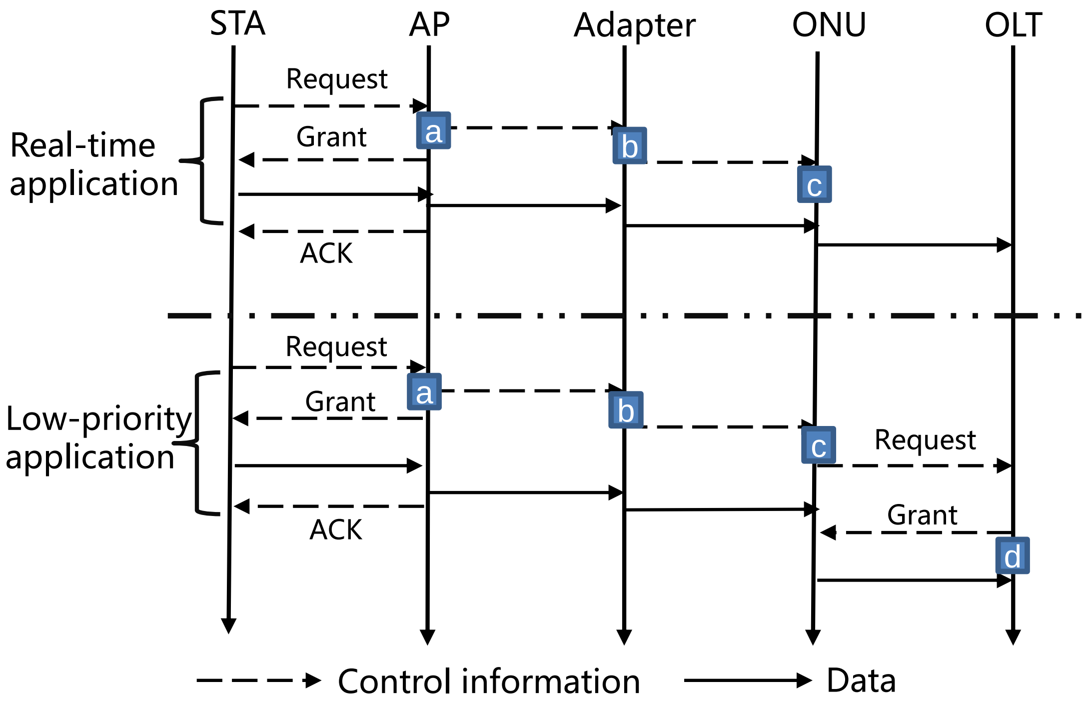
Cooperation between PON and WiFi

- **Traffic mapping**
  - Map WiFi access category to PON service priority
- **Traffic shaping**
  - Responsible for frame aggregation to increase network throughput
- **Synchronization**
  - Synchronize scheduling between WiFi and PON

N. Ghazisaidi, et al., "Hierarchical Frame Aggregation Techniques for Hybrid Fiber-Wireless Access Networks," IEEE Communication Magazine, 2011.

Scheme 2: Cooperative resource scheduling

➢ **To improve bandwidth utilization subject to different latency requirements**



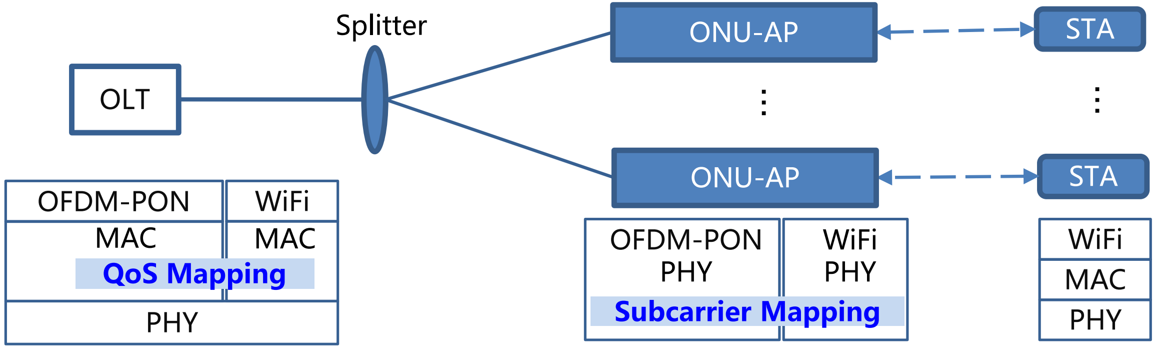
a **Access control:** Real-time applications have a high priority

b **Traffic mapping and shaping:** Data from real-time applications is forwarded directly to reduce delay, while that from low-priority applications needs to be aggregated to improve network throughput

c **Resource allocation at ONU:** A certain amount of bandwidth is reserved for real-time applications, while other bandwidth is allocated dynamically to low-priority applications to improve bandwidth utilization

d **Resource allocation at OLT:** Bandwidth is allocated dynamically to ONUs

Scheme 3: PHY-layer integrated architecture



OLT: Optical line terminal

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AP: Access point

STA: Station

➢ **AP and ONU are integrated in PHY layer**

- **Advantage:** WiFi signal can be transmitted without MAC-layer processing at an integrated ONU-AP. Thus, signal processing time, bandwidth overhead used for frame encapsulation and the cost of integrated devices can be further reduced.

W. Lim, et al., "MAC Protocol Designs for OFDMA-PONs," IEEE ISCIT, 2014.

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Water filling based resource allocation

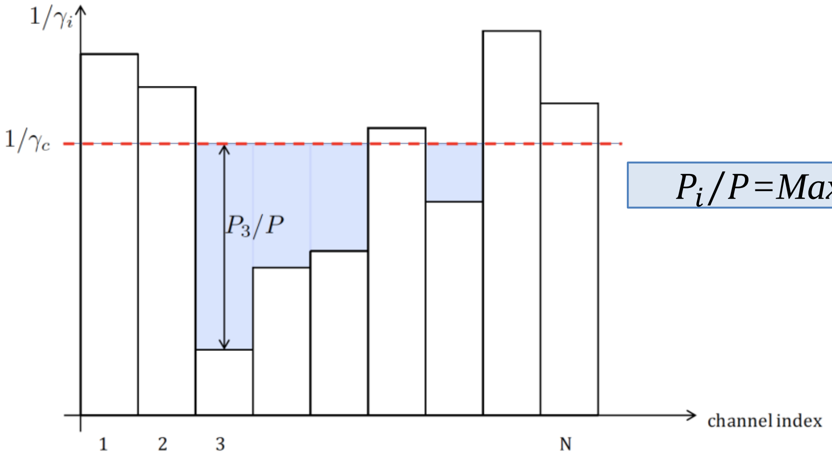
➢ Water filling based power allocation in OFDM system

- Power is allocated to the subcarrier with the best channel quality

γ: Signal noise ratio

P: Total power

P_3: Power allocated to the third subcarrier



$$P_i/P = Max\,(1/\gamma_c - 1/\gamma_i\,, 0)$$

OFDM-PON：Bit-loading

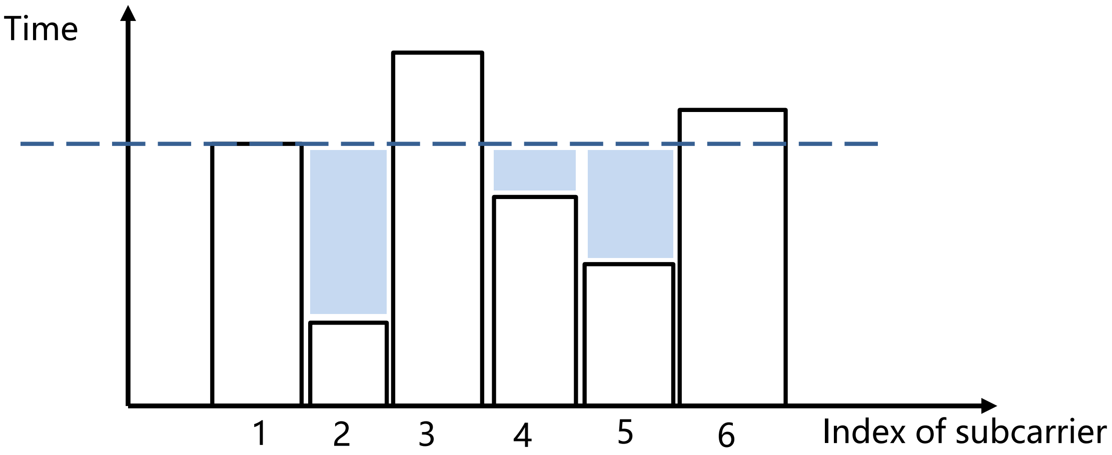
Conventional water filling algorithms cannot be used for time-domain resource allocation, and cannot well support real-time services

R. S. Prabhu, et al., "An Energy-Efficient Water-Filling Algorithm for OFDM Systems," 2010 IEEE International Conference on Communications, 2010

Water filling based resource allocation

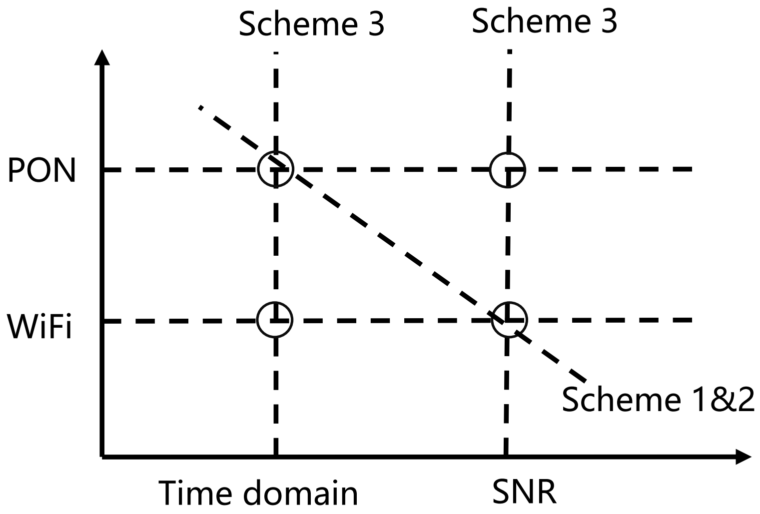
➢ Water filling based resource allocation in OFDM-PON

- Each ONU can be allocated with multiple subcarriers, while each subcarrier occupies different time slots for data transmission
- Subcarrier with few occupied time slots has high priority to be chosen



Water filling based resource allocation

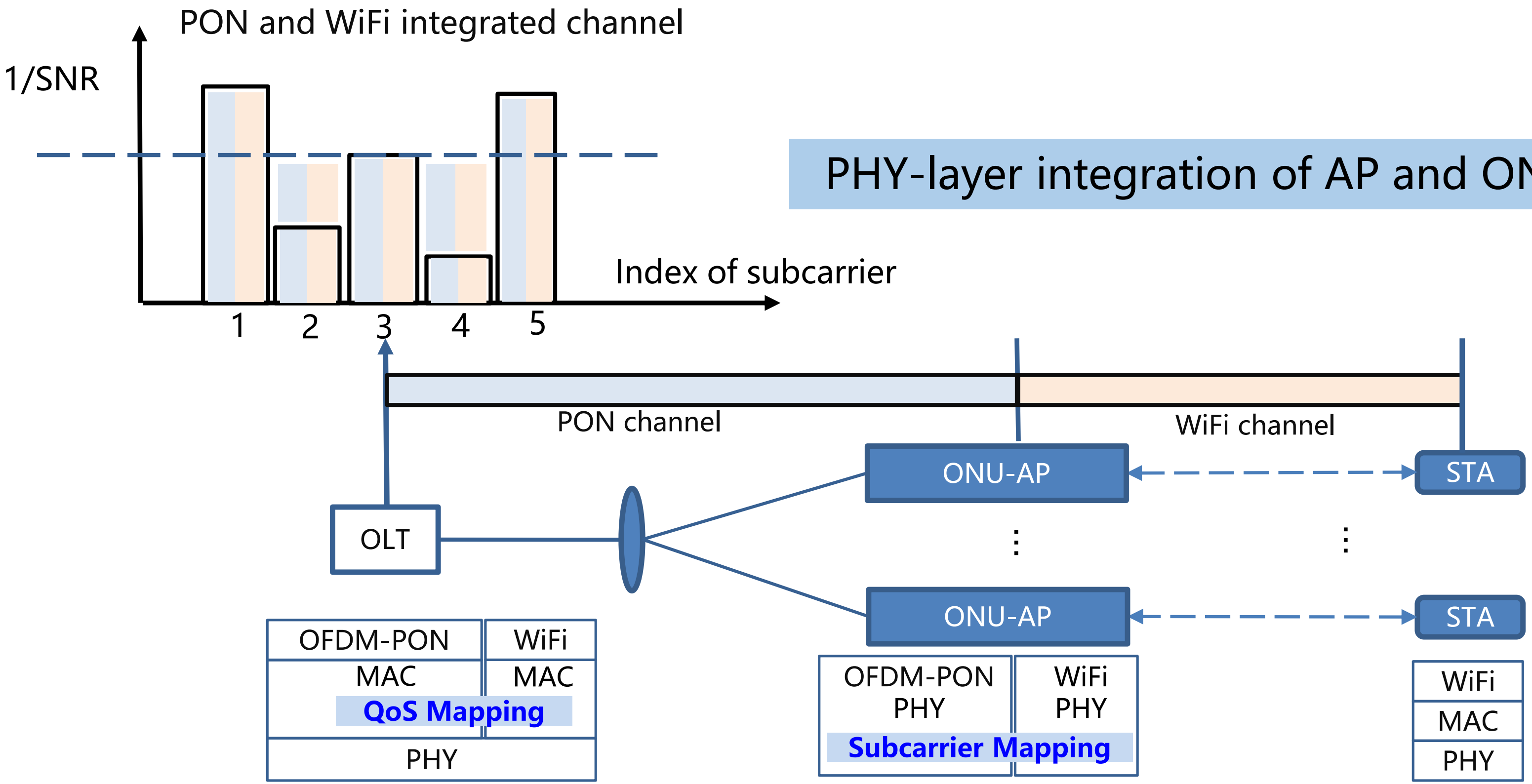
➢ **Water filling based resource allocation in OFDM-PON and WiFi integrated access network**



Scheme	PON	WiFi
1	Time domain	SNR
2	Time domain	SNR
3	Time domain	Time domain
	SNR	SNR

SNR : Signal noise ratio

Scheme 3: PON（SNR）+ WiFi（SNR）



PHY-layer integration of AP and ONU

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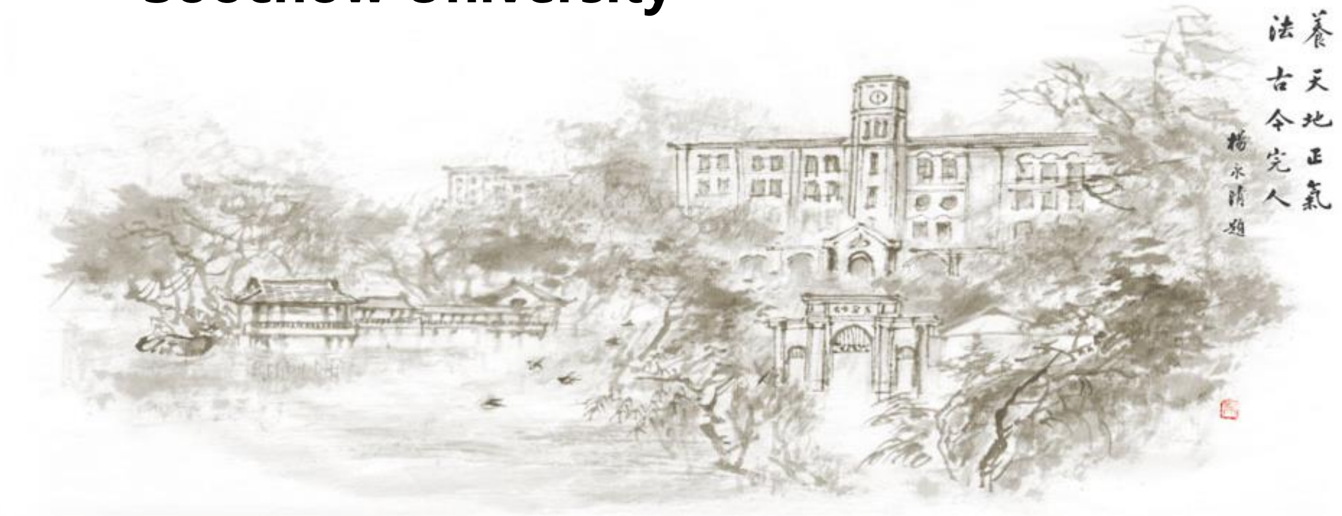


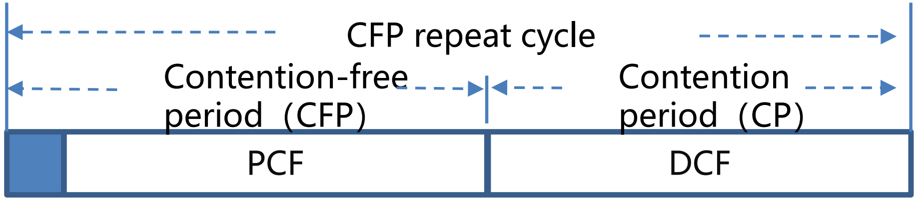
Features of WiFi 7

	Nominal Throughput	Interference Mitigation	Spectrum Efficiency	Real-time application
EHT PHY	4096QAM, 320MHz, Mu-MIMO		EHT Preamble	
EDCA with 802 TSN Features				IEEE 802 TSN, Faster Backoff, New Access Categories, TXOP capturing
Enhanced OFDMA		Preamble Puncturing	Multi-RU, Direct links	Enhanced UORA
Multi-link Operation	Multi-link Architecture	Synchronous Channel Access	Virtual BSS	Asynchronous Channel Access, Packet Duplication, Queue Management, Dynamic Link Switching
Channel Sounding Optimization			Implicit Sounding, Explicit Feedback Channel Estimation	
Advanced HY	Full Duplex		HARQ NOMA/SOMA	
Multi-AP Cooperation		Null steering Co-OFDMA CSR		Joint Reception

E. Khorov, et al., “Current Status and Directions of IEEE 802.11be, the Future Wi-Fi 7,” IEEE Access, April, 2020.

WiFi access control

- **Two basic working modes without guaranteeing quality of service (QoS) are designed in IEEE 802.11media access control (MAC) layer**
  - **Distributed coordination function (DCF):** a carrier sense multiple access with collision avoidance (CSMA/CA) scheme with binary slotted exponential backoff
  - **Point coordination function (PCF):** a contention-free access method based on a polling scheme controlled by AP，which is the extension of DCF.



- **IEEE 802.11 modifies the MAC layer by adding EDCA and HCCA to support QoS**
  - **Enhanced distributed channel access (EDCA):** a contention based channel access method, which can provide differentiated service
  - **Hybrid coordination function controlled channel access (HCCA):** a contention-free access method, in which service priority is introduced in polling procedure and QoS can be supported

A. Malik, et al., "QoS in IEEE 802.11-based Wireless Networks: A Contemporary Survey," arXiv:1411.2852v1, 2014.

WiFi access category

- **IEEE 802.11 has four access categories: Background, Best Effort, Video and Voice, while user service has 8 queuing priorities that need to be mapped to access categories.**

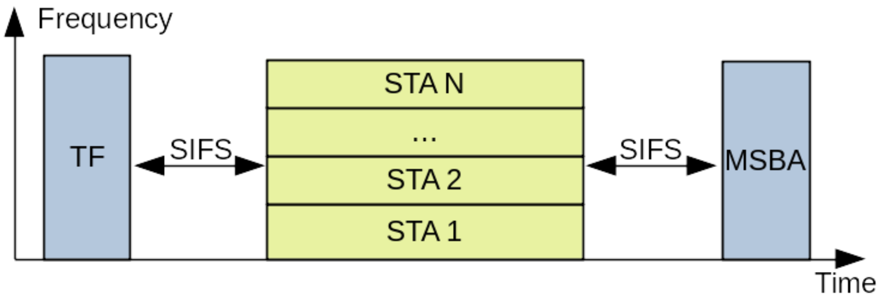
Priority	User priority	Access category
Low	0	Best Effort
	1	Background
	2	Background
	3	Video
	4	Video
	5	Video
	6	Voice
High	7	Voice

- ✓ **The existing access category cannot satisfy the requirements of emerging services**
  - Real time application（RTA）e.g., cloud VR
- ✓ **EDCA or HCCA based access control cannot provide determistic QoS for RTA**
  - IEEE 802.11be has discussed to introduce new access category

A. Malik, et al., "QoS in IEEE 802.11-based Wireless Networks: A Contemporary Survey," arXiv:1411.2852v1, 2014.

Orthogonal frequency-division multiple access

- **IEEE 802.11ax introduces orthogonal frequency-division multiple access (OFDMA), which is a key technology to support real-time services**



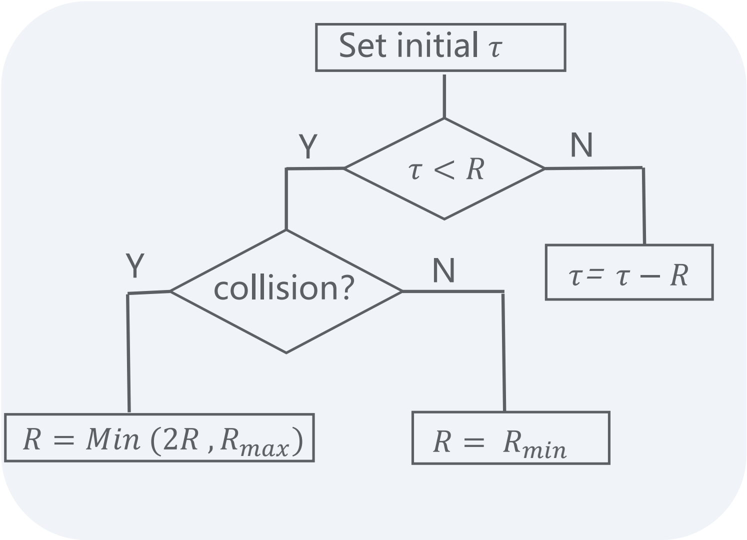
- **Multiple stations(STAs)can receive/send data simultaneously**
  - Access point periodically broadcasts trigger frame (TF) with resource scheduling information to STAs
  - Once receiving TF, STAs wait short inter-frame space (SIFS) and transmit data to the AP
  - Once receiving data, the AP waits SIFS and sends acknowledge message to STAs
- Spectrum resource can be allocated to STAs according to Uplink OFDM random access (UORA)

E. Khorov, et al., "A Tutorial on IEEE 802.11ax High Efficiency WLANs," IEEE Communication Survey & Tutorials, vol. 21, no. 1, 2019.

Uplink OFDMA random access

Uplink OFDMA random access (UORA)

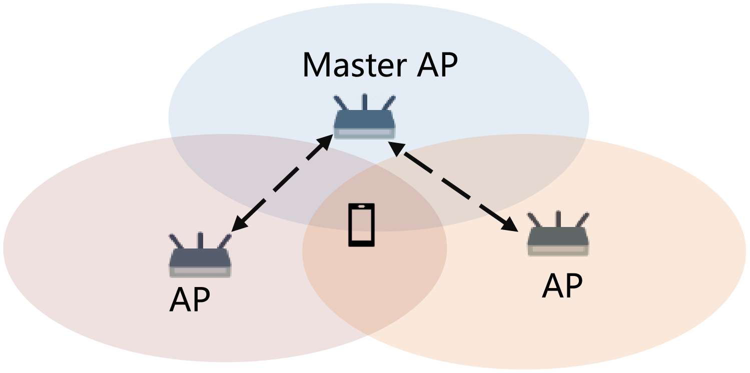
- Each STA that has data to be transmitted is allocated with a random value (τ), $\tau \in \{0,1,2 \ldots W-1\}$, W is OFDMA contention window
- Once receiving the trigger frame, the STA obtains the information about the total amount of available resource (R), then compare τ with R
- If $\tau < R$, the AP randomly selects a RU for the STA. Otherwise, $\tau = \tau - R$, the STA waits the next trigger frame
- If a collision occurs, the STA resets $R = Min\,(2R\,, R_{max})$, in which R_{max} is the maximum contention window
- If the data is transmitted successfully, the STA decreases the contention window to the minimum value (R_{min})



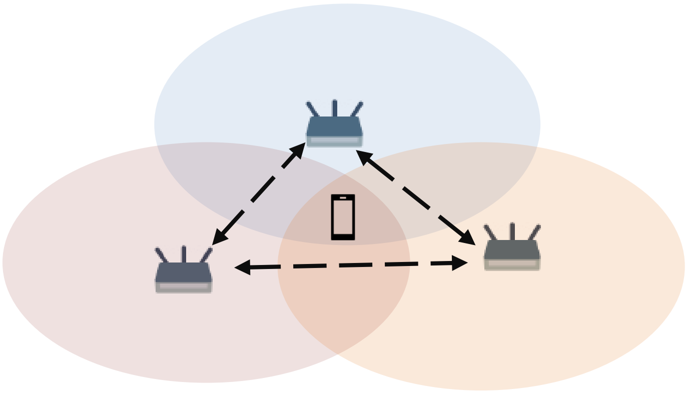
E. Khorov, et al., "A Tutorial on IEEE 802.11ax High Efficiency WLANs," IEEE Communication Survey & Tutorials, vol. 21, no. 1, 2019.

Multi-AP Cooperation

- Multi-AP cooperation is regarded as one of the key technologies for next generation WiFi (WiFi 7)
  - **High spectrum efficiency**
  - **Support real-time services**
- Both centralized and distributed multi-AP cooperation have stringent requirements on backhaul networks



Centralized multi-AP cooperation

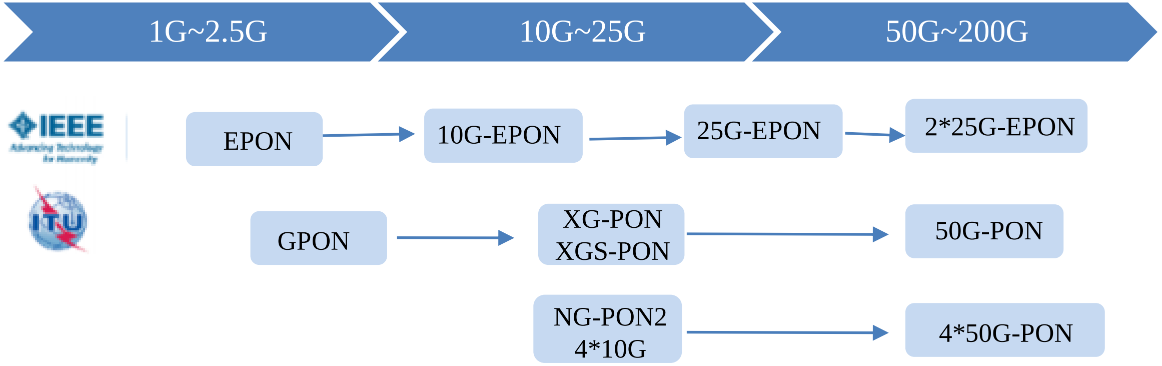


Distributed multi-AP cooperation

E. Khorov, et al., “Current Status and Directions of IEEE 802.11be, the Future Wi-Fi 7,” IEEE Access, May 2020.

Passive optical network

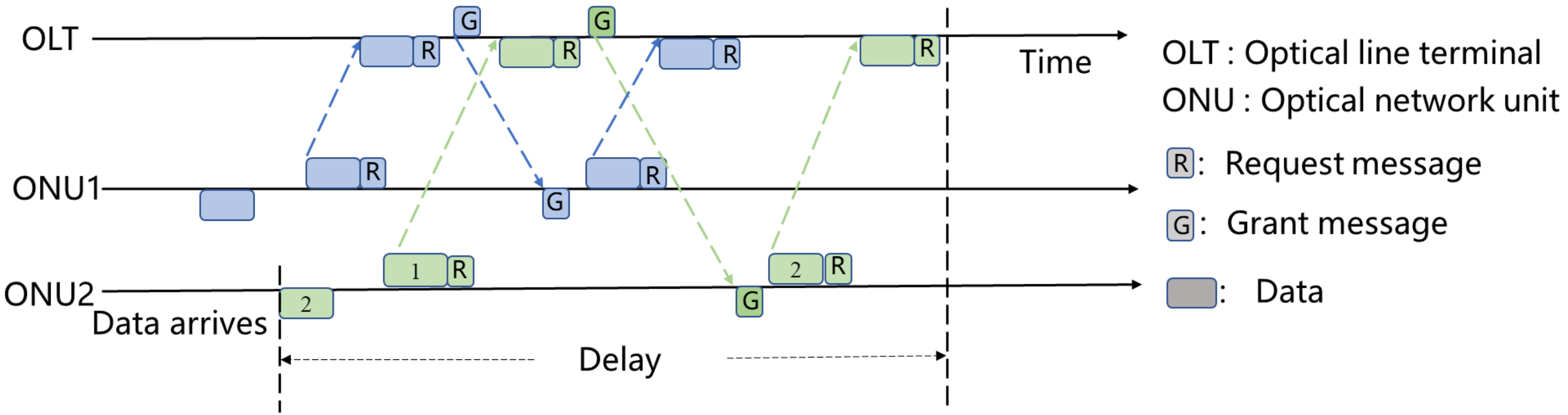
- Passive optical network is a point to multi-point architecture, in which optical network units (ONUs) can share one optical distribution network via time division multiplexing(TDM), wavelength division multiplexing (WDM) and orthogonal frequency division multiplexing (OFDM)
- TDM-PON is widely deployed, and has evolved to meet the requirements of emerging services, which includes GPON and EPON



Real-time services have a stringent latency requirement on TDM-PON

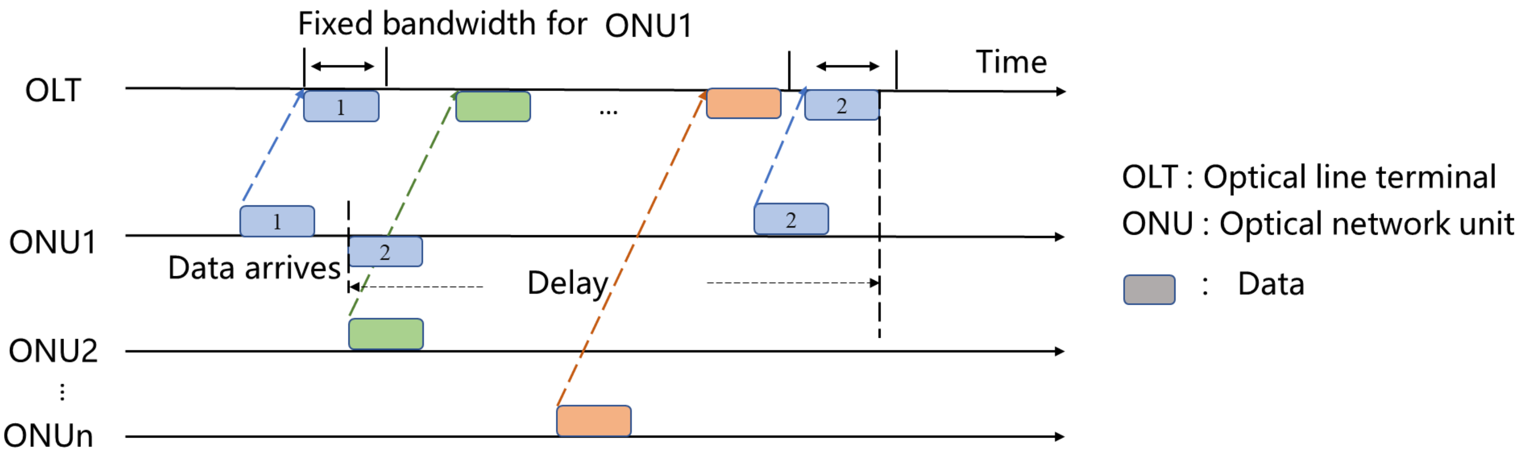
TDM-PON

- In TDM-PON, upstream bandwidth is shared by multiple optical network units (ONUs)
- Even though Report/Grant based dynamic bandwidth allocation method can improve bandwidth utilization, it also brings a **high upstream delay**.



TDM-PON

- In TDM-PON, fixed bandwidth method can avoid the delay that is induced by Report/Grant mechanism, but the waiting delay during polling procedure can not be avoided and bandwidth utilization may be degraded.



Waiting delay during polling procedure is still a bottleneck for TDM-PON to support real-time services

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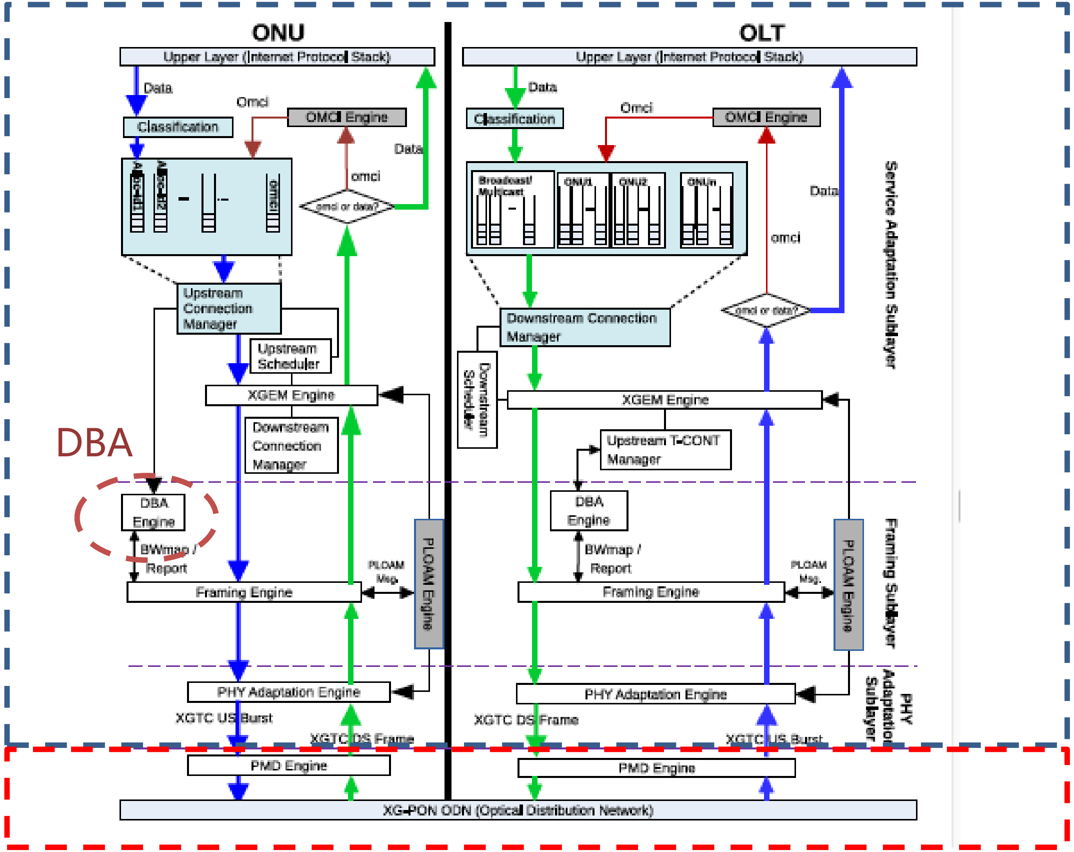
  - PON simulation platform

Function block diagram of XG-PON

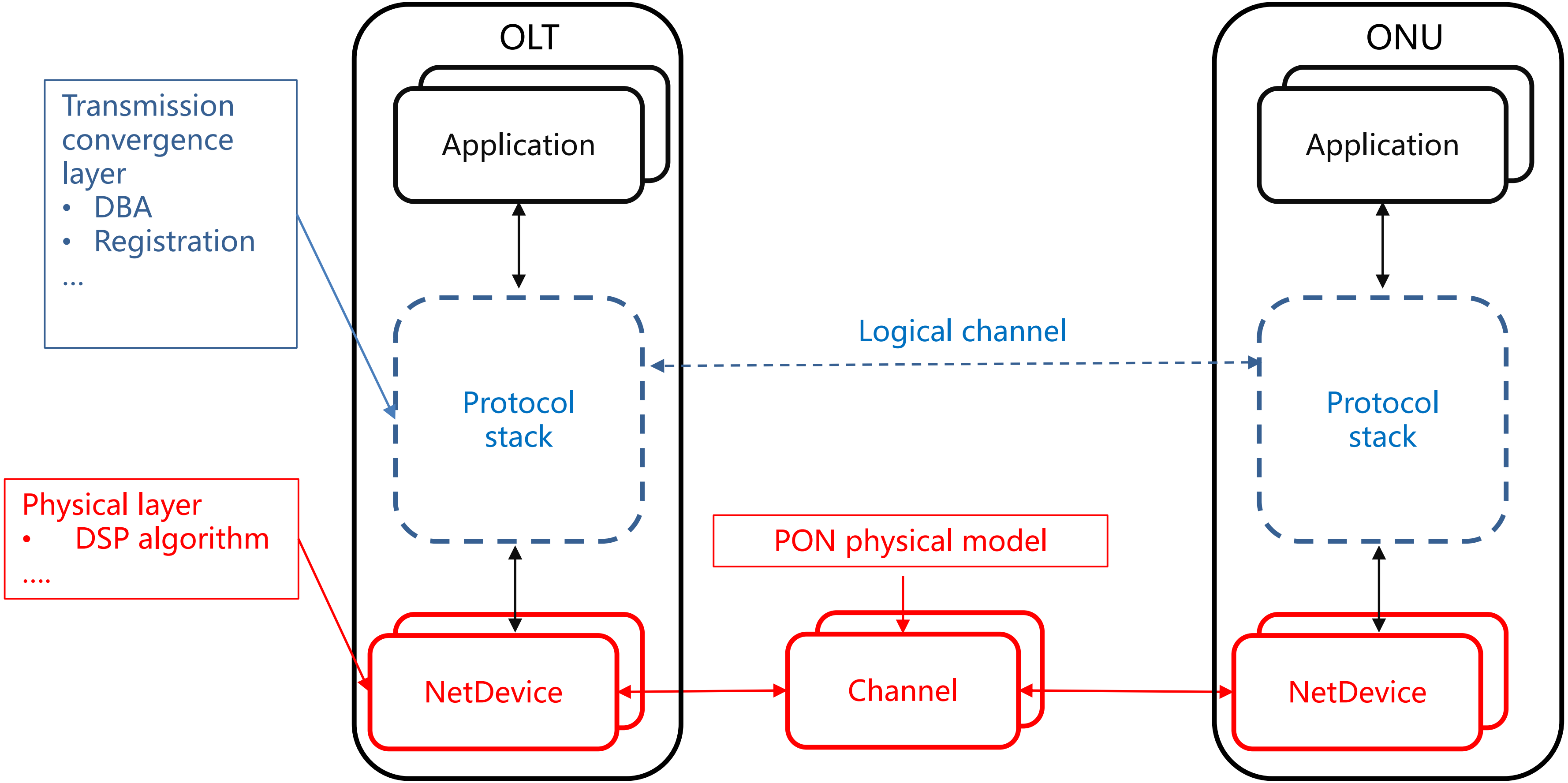
Transmission convergence layer

Physical layer



X. Wu, et al., “An XG-PON Module for the NS-3 Network Simulator,” in Proceedings of ICST, Brussels, 2013, 195-202

Diagram of PON simulator based NS3



Simulation parameters for resource allocation

TABLE I:
SDSCA DESIGN PARAMETERS.

<table>
<tr><th>Parameters</th><th colspan="2">Description</th></tr>
<tr><td>Total network capacity</td><td colspan="2">10 Gbps</td></tr>
<tr><td>Number of subcarriers</td><td colspan="2">64</td></tr>
<tr><td>Data rate per subcarriers</td><td colspan="2">156.25 Mbps (10 Gbps / 64)</td></tr>
<tr><td>Number of time slots per subcarrier</td><td colspan="2">6</td></tr>
<tr><td>Data rate per time slots</td><td colspan="2">25.375 Mbps (10 Gbps / 64 / 6)</td></tr>
<tr><td rowspan="2">Number of ONUs</td><td colspan="2">32</td></tr>
<tr><td colspan="2">$SLA_0 : SLA_1 : SLA_2 = 2 : 10 : 20$</td></tr>
<tr><td rowspan="3">Guaranteed Data Rate per SLA (SLA_TS)</td><td>SLA_0</td><td>468.75 Mbps (3 subcarriers)</td></tr>
<tr><td>SLA_1</td><td>312.5 Mbps (2 subcarriers)</td></tr>
<tr><td>SLA_2</td><td>156.25 Mbps (1 subcarrier)</td></tr>
<tr><td>Distance between OLT and ONU</td><td colspan="2">20 km</td></tr>
<tr><td>Monitoring window time</td><td colspan="2">1.0 ms</td></tr>
<tr><td>Grant processing delay</td><td colspan="2">5 µs</td></tr>
<tr><td>Propagation delay</td><td colspan="2">5 µs/km</td></tr>
<tr><td>ONU offered load 1.0</td><td colspan="2">312.5 Mbps (10 Gbps / 32)</td></tr>
<tr><td>Network offered load 1.0</td><td colspan="2">10 Gbps</td></tr>
<tr><td>Packet size</td><td colspan="2">64 – 1518 Bytes
(Uniformly generated)</td></tr>
<tr><td rowspan="3">Traffic generation of CoSs</td><td colspan="2">High priority CoS0: 20 %</td></tr>
<tr><td colspan="2">Middle priority CoS1: 40 %</td></tr>
<tr><td colspan="2">Low priority CoS2: 40 %</td></tr>
</table>

W. Lim, et al., “MAC Protocol Designs for OFDMA-PONs,” IEEE ISCIT, 2014.