# QoE Management of Multimedia Streaming Services in Future Networks: A Tutorial and Survey

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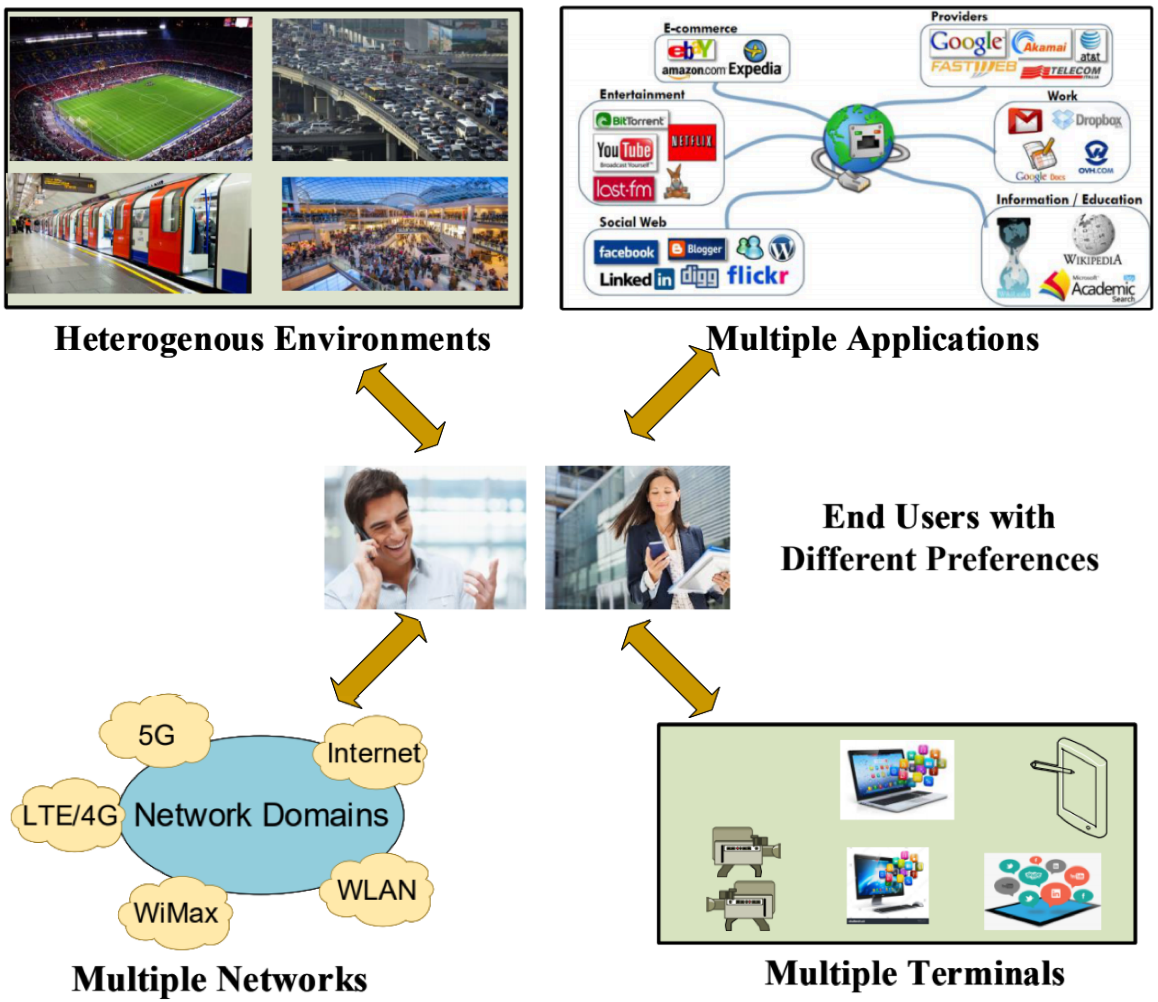
IEEE Communications Surveys & Tutorials

# QoE Management Challenges in Future Networks



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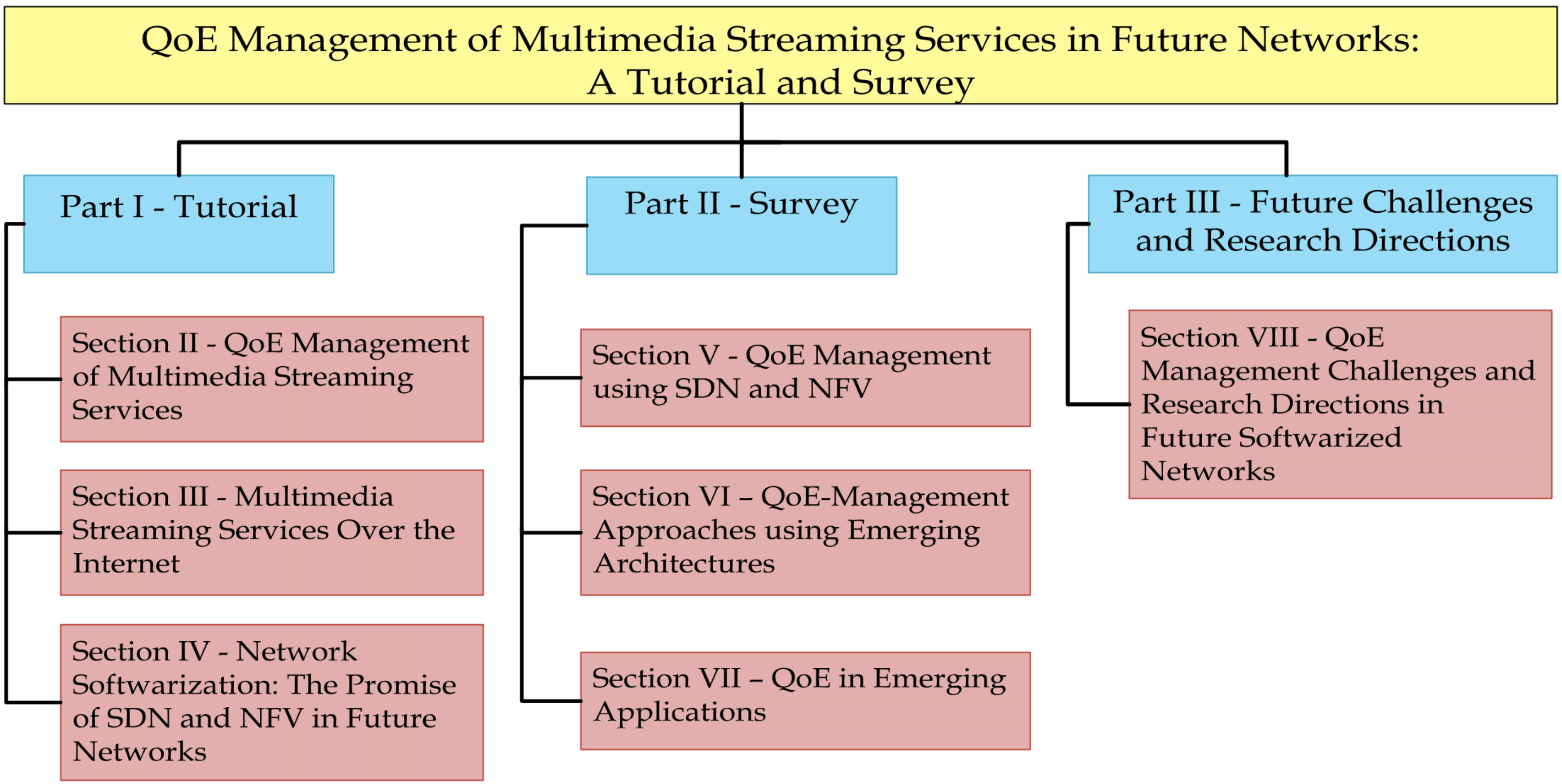

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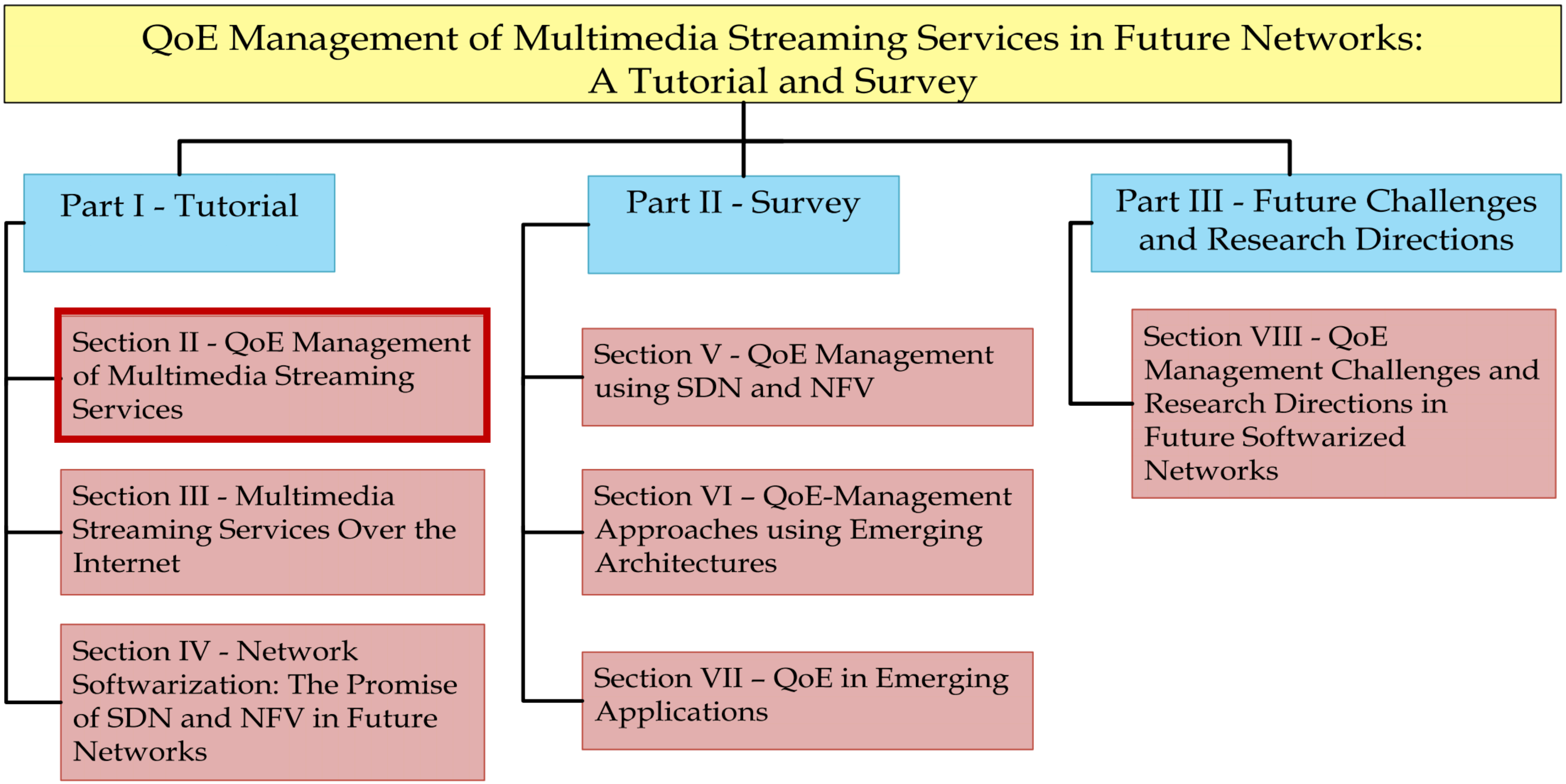

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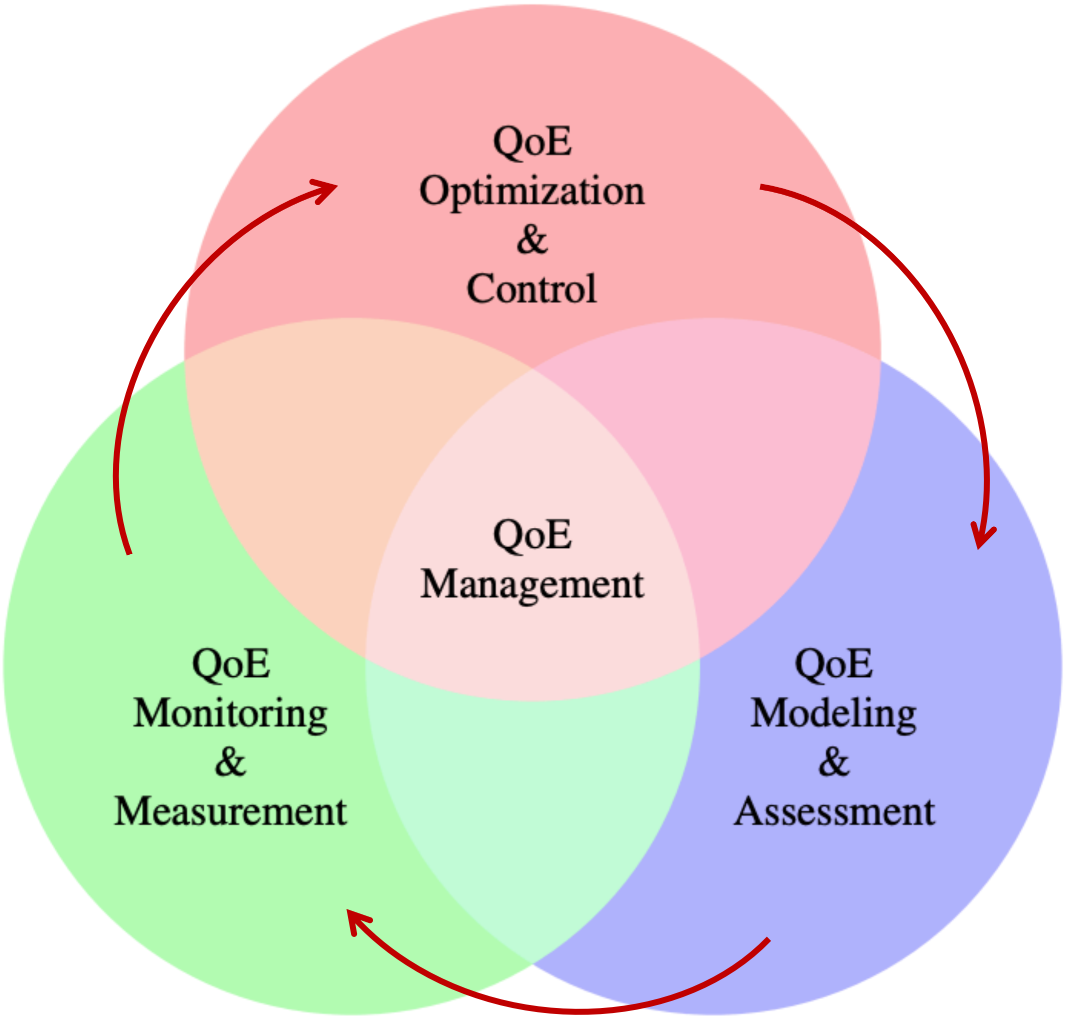

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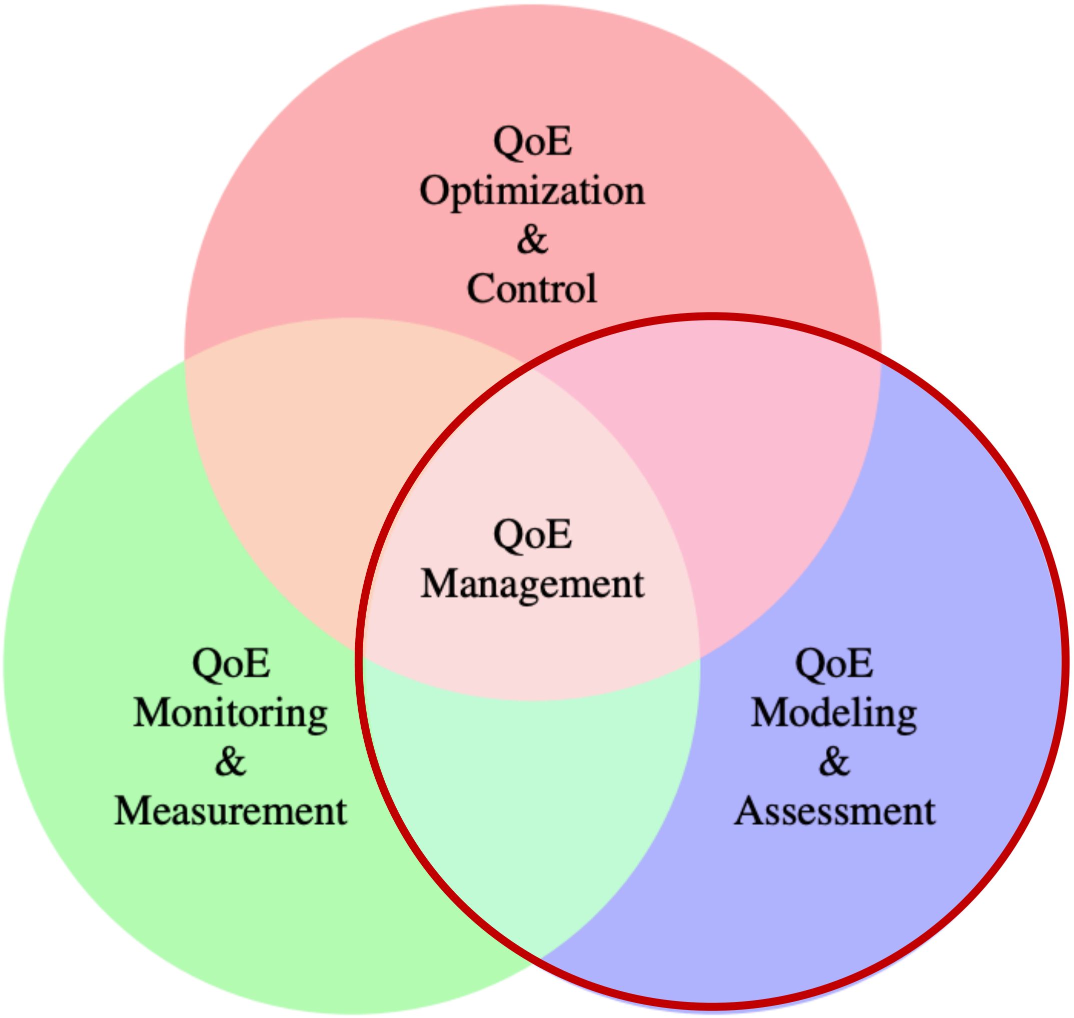


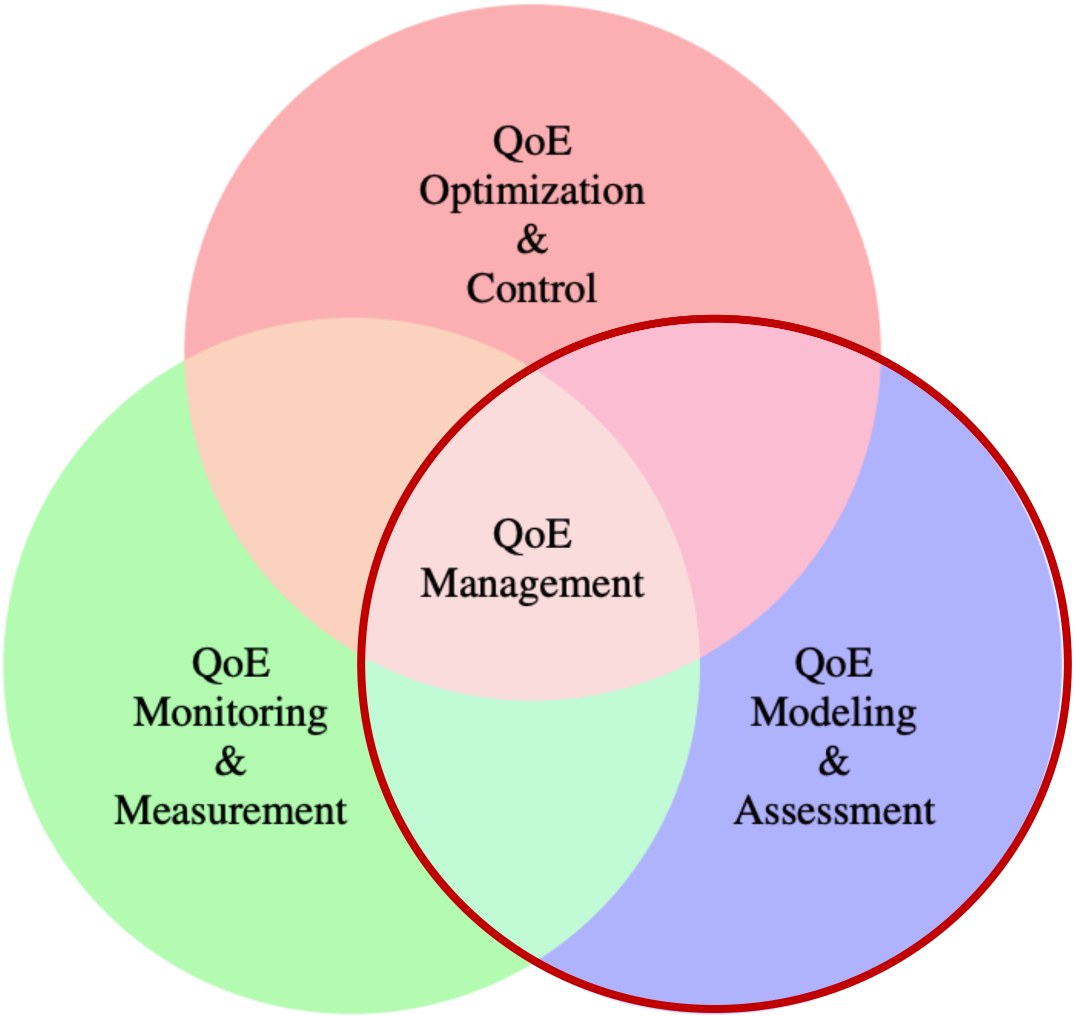
# QoE Modeling and Assessment

- *The process of measuring or estimating the QoE for a set of users of an application or service with a dedicated procedure and considering the influencing factors*
- One of the essential steps toward QoE-based monitoring and management
- Methods and guidelines are described in the ITU-T Rec. BT.500 [41], P.910 [42] and P.913 [43]

# Commonly Used Image and Video QA Models

| Metric | Year | Model Type | Modality |
|---|---|---|---|
| Peak Signal-to-Noise Ratio (PSNR) [49] | | FR | Images - Frames |
| Structural Similarity Index Metric (SSIM) [44] | 2004 | FR | Images - Frames |
| Video Multimethod Assessment Fusion (VMAF) [45] | 2016 | FR | Images - Frames |
| Visual Information Fidelity (VIF) [50] | 2006 | FR | Images - Frames |
| HDR-VDP-2: A calibrated visual metric for visibility and quality predictions in all luminance conditions [51] | 2011 | FR | HDR images |
| Video Quality Metric (VQM) [52] | 2004 | FR | Video |
| Reduced Reference Entropic Differencing (RRED) [53] | 2013 | RR | Video |
| Spatial Efficient Entropic Differencing for Quality Assessment (SpEED-QA) [54] | 2017 | RR | Video |
| Blind Image Quality Index (BIQI) [55] | 2010 | NR | Images - Frames |
| Blind/Referenceless Image Spatial QUality Evaluator (BRISQUE) [56] | 2012 | NR | Images - Frames |
| Naturalness Image Quality Evaluator (NIQE) [57] | 2013 | NR | Images - Frames |
| HDR Image GRADient based Evaluator (HIGRADE) [58] | 2017 | NR | HDR images |

# QoE Management for Multimedia Streaming Services



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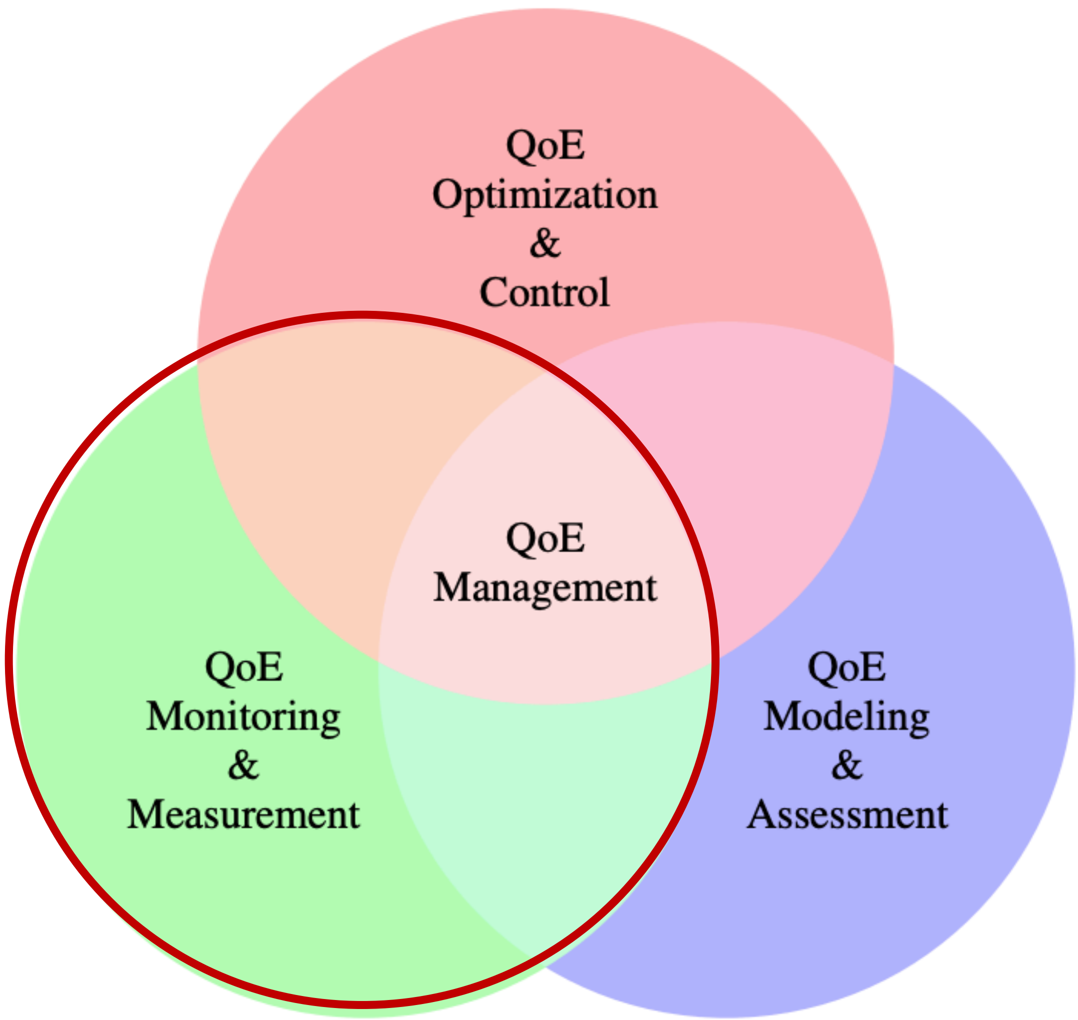
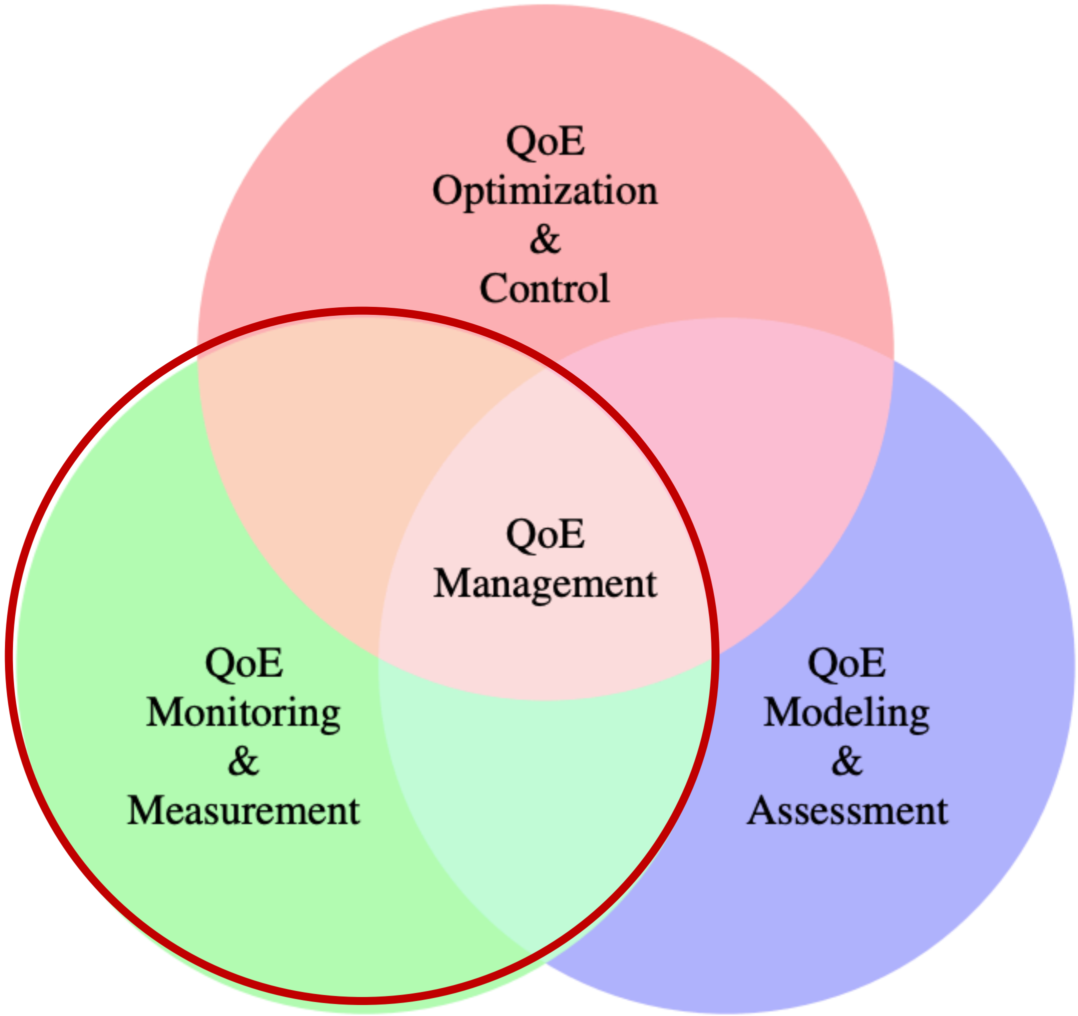


# QoE Monitoring and Measurement

- Understanding the root cause of QoE degradation or unsatisfactory QoE levels
- Measuring the relevant information and data e.g., terminal capabilities, application/service specific information, and QoE-related information inside the network
- The collected Key Performance Indicators (KPIs) provide inputs for QoE estimation models
  - Network-level: throughput, packet loss, delay
  - User-level service/application specific: frame rate, video resolution, service usability, and reliability

# QoE Management for Multimedia Streaming Services



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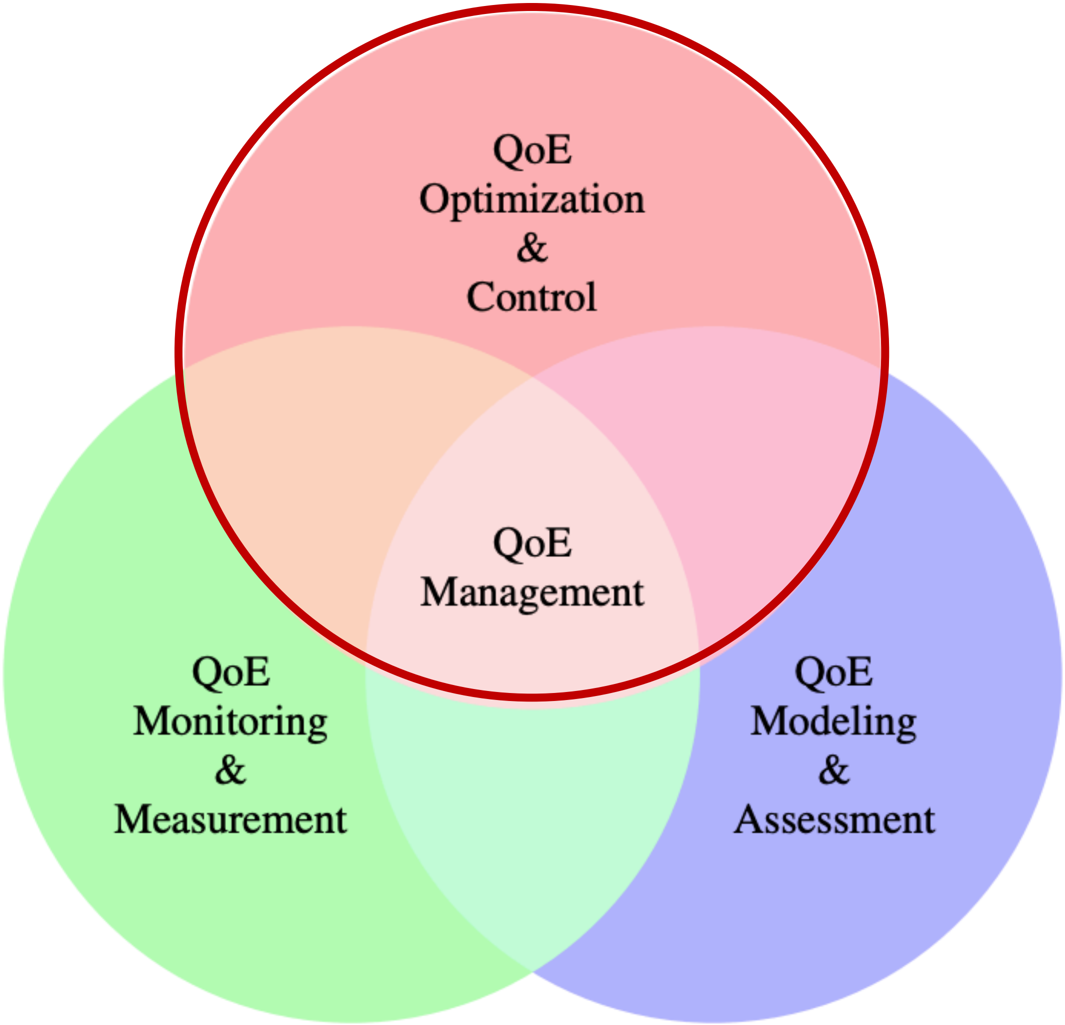
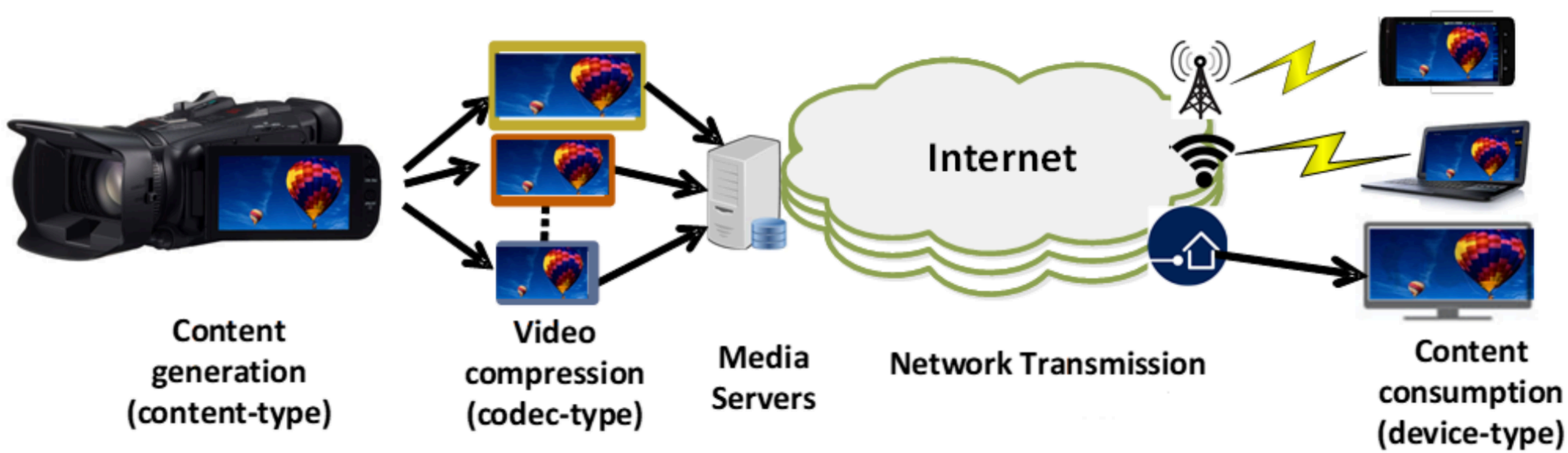


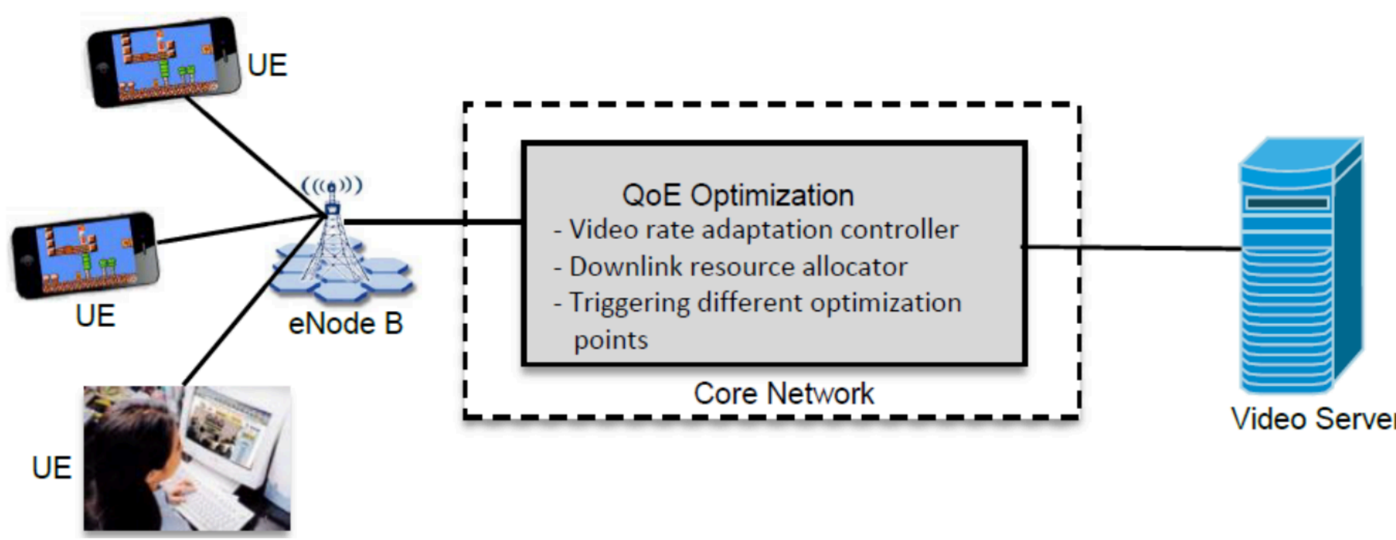
# QoE Optimization and Control

- Maximize the end users' QoE level through the efficient allocation of available network resources
  - What key quality parameters to optimize and control?
  - Where to control?
  - When to perform QoE optimization and control?
  - How often to control and optimize QoE?



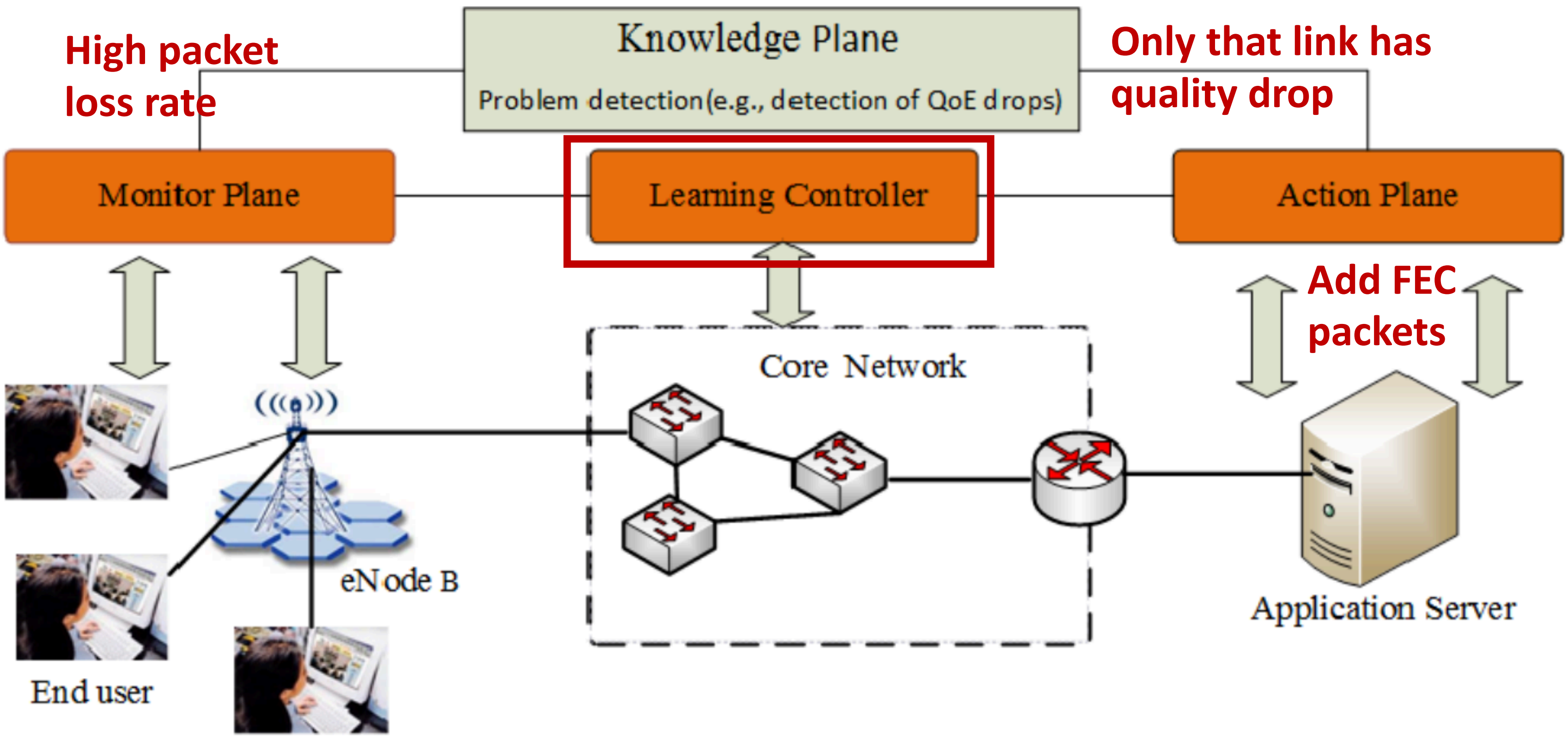
# Literature of QoE Management

- Service adaptation and resource allocation [62-70]
  - Given QoE related information (e.g., network level or service level) collected from QoE monitoring and measurement
    → perform resource allocation and service adaptation
    ⇒ provide quality assurance and service control



# Literature of QoE Management

- Autonomic architecture optimization [71]

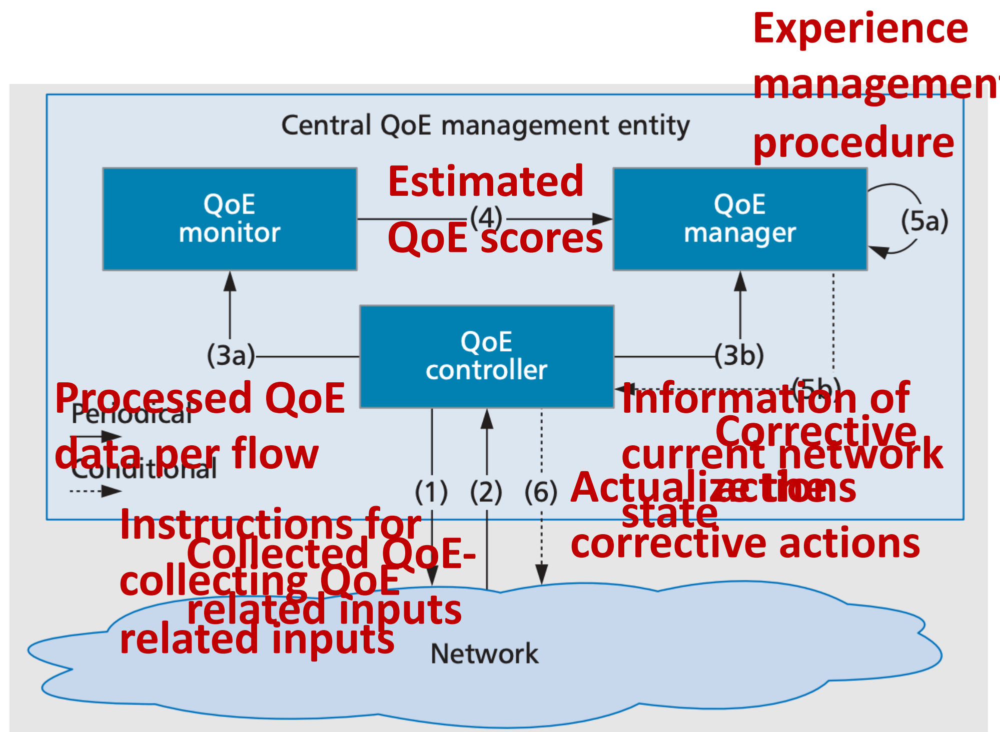


# Literature of QoE Management

- Incorporate machine learning-based mechanisms
  - online learning, e.g., Q-learning, to find the best actions on a particular service until a better quality is achieved [72]
  - Maximize the QoE using Convolutional Neural Network (CNN) [73]

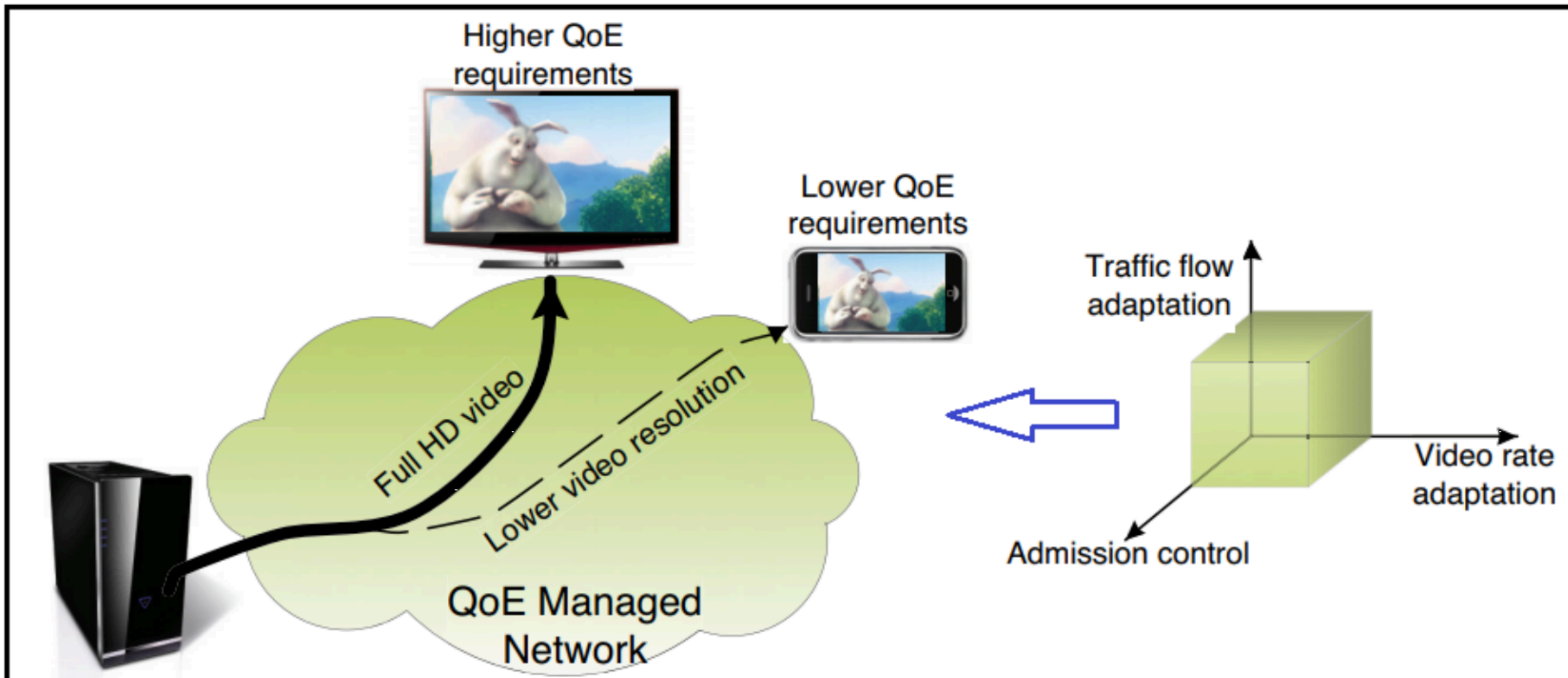
# Literature of QoE Management

- Joint network resource allocation and service adaptation
  - Video quality adaptation -> maximize the client's QoE [74][79][80][81][82]
  - Minimize energy consumption [75][76]
  - Adapt the quality according to the available throughput and HAS QoE metric [77][78]



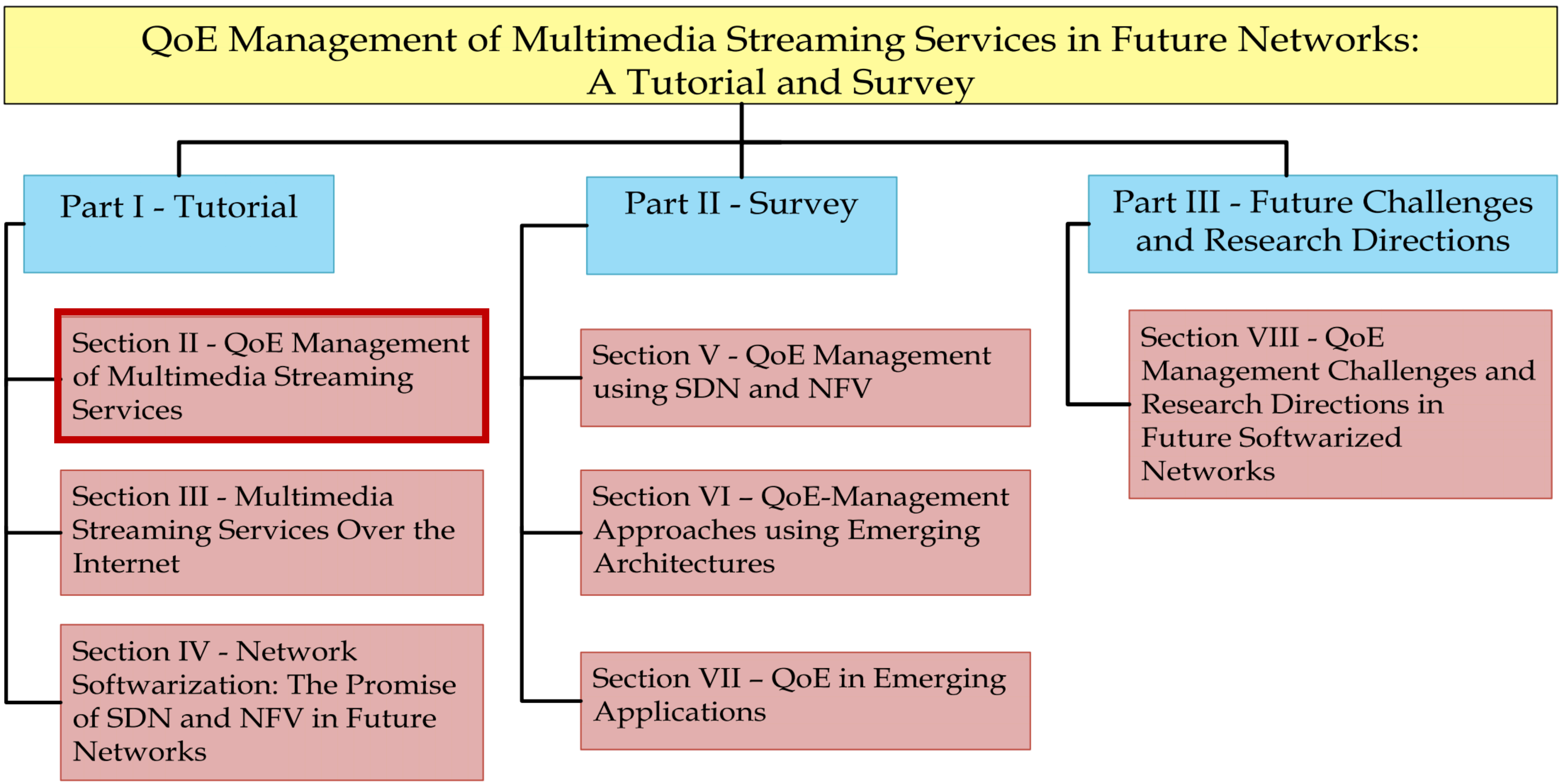
# Literature of QoE Management

- Maximize QoE using traffic flow adaptation, admission control, and video rate adaptation [86]



# QoE Optimization can be Performed

- At various points
  - base stations within the access networks [87]–[91]
  - end-user device (e.g., battery consumption) [94]
  - different levels ranging from link to application-layer [95], [64]
- Using different QoE mechanisms
  - common cross-layer approach [67], [68], [90], [91], [83], [96]
  - conducting adjustments of servers in the service/application [71], [91]–[93]
  - applying QoE-based policy management within the core networks [67], [68], [90], [91]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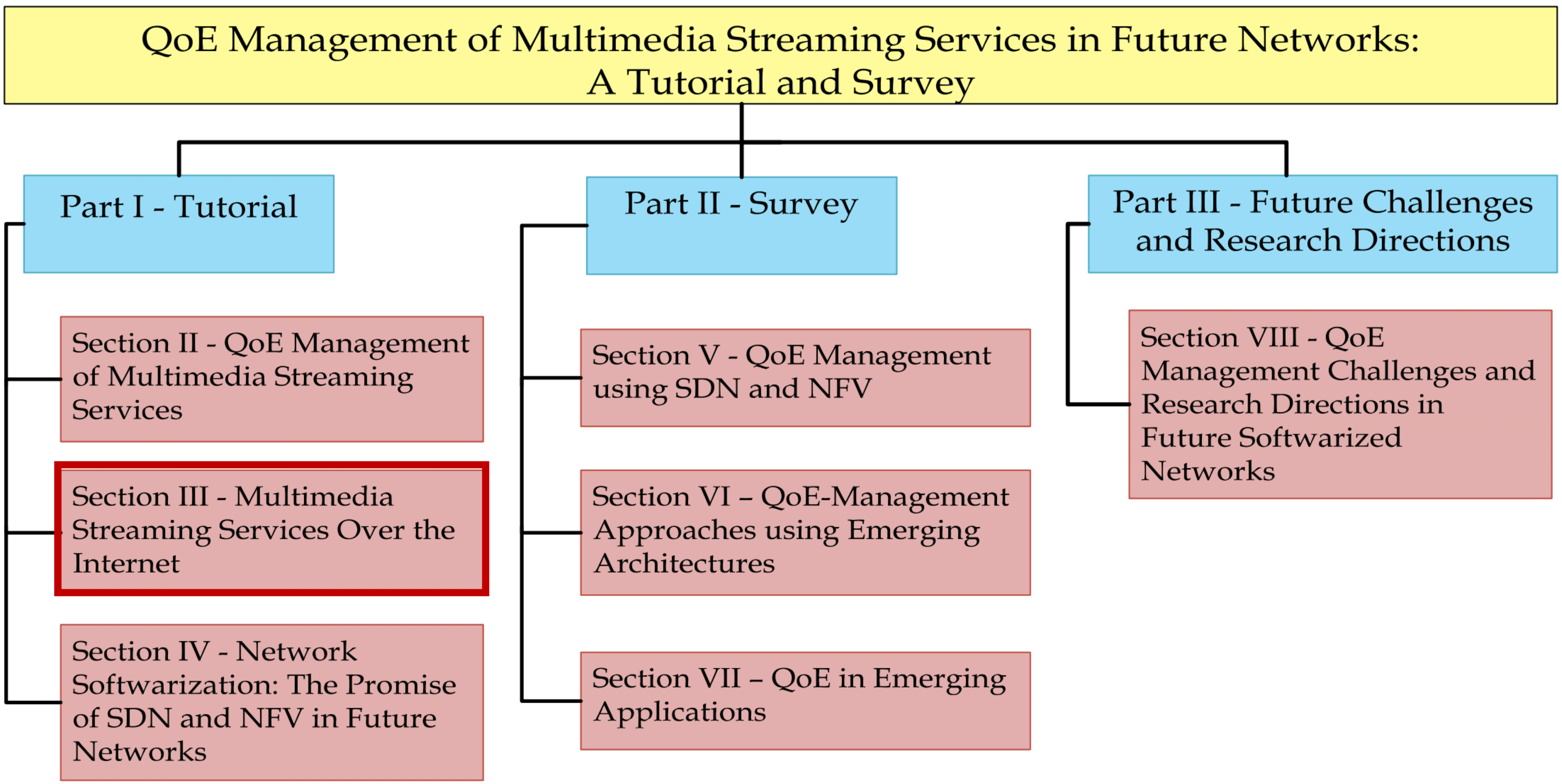
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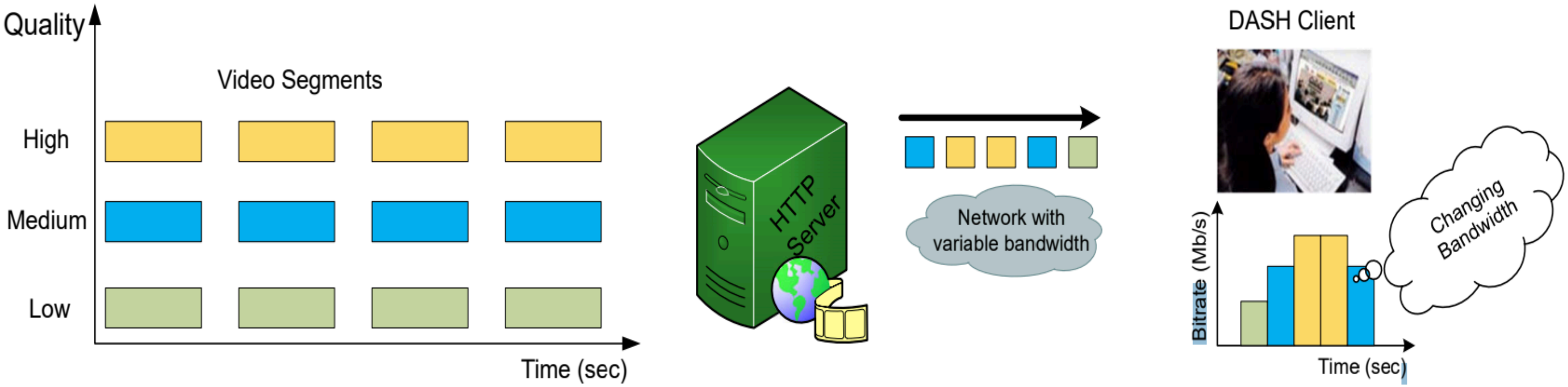
# HTTP Adaptive Streaming (HAS) Solutions

- The majority of Internet video traffic today is delivered via HAS
  - providing a reliable transmission
  - cache infrastructure reuse capability
  - enabling firewall traversal

| HAS Category | Company | Video Codec | Segment Length (sec) | Data Description | Format |
|---|---|---|---|---|---|
| Microsoft Smooth Streaming [97] | Microsoft Corporation | H.264, VC-1 | 2 | Manifest (XML) | fMP4 |
| Apple HTTP Live Streaming (HLS) [98] | Apple Inc. | H.264 | 10 | Playlist file (M3U8) | M2TS, *.ts files |
| Adobe HTTP Dynamic Streaming (HDS) [99] | Adobe Systems Inc. | H.264, VP6 | 2 - 5 | Manifest (F4M) | fMP4 |
| MPEG-DASH [100] | Standard | Any | Not specified | Media Presentation Description (MPD) files (XML) | MP4 or M2TS |
| 3GP-DASH [101] | Standard | H.264 | Not specified | MPD files (XML) | 3GPP File Format |

- HAS has been widely used in Over-The-Top-Provider (OTTP) video services such as Netflix and YouTube
- Delivery mechanisms
  - TCP or Quick UDP Internet Connection (QUIC)

# Dynamic Adaptive Streaming over HTTP (DASH)




- Video service providers can offer multiple quality levels to the end-users' demands by adapting video bitrates
- Different QoE-tailored personalized service levels and/or pricing schemes can be offered to customers

# Drawbacks of DASH with Multiple DASH Clients

- Video instability due to bitrate switching
- Network resource underutilization
- QoE unfairness

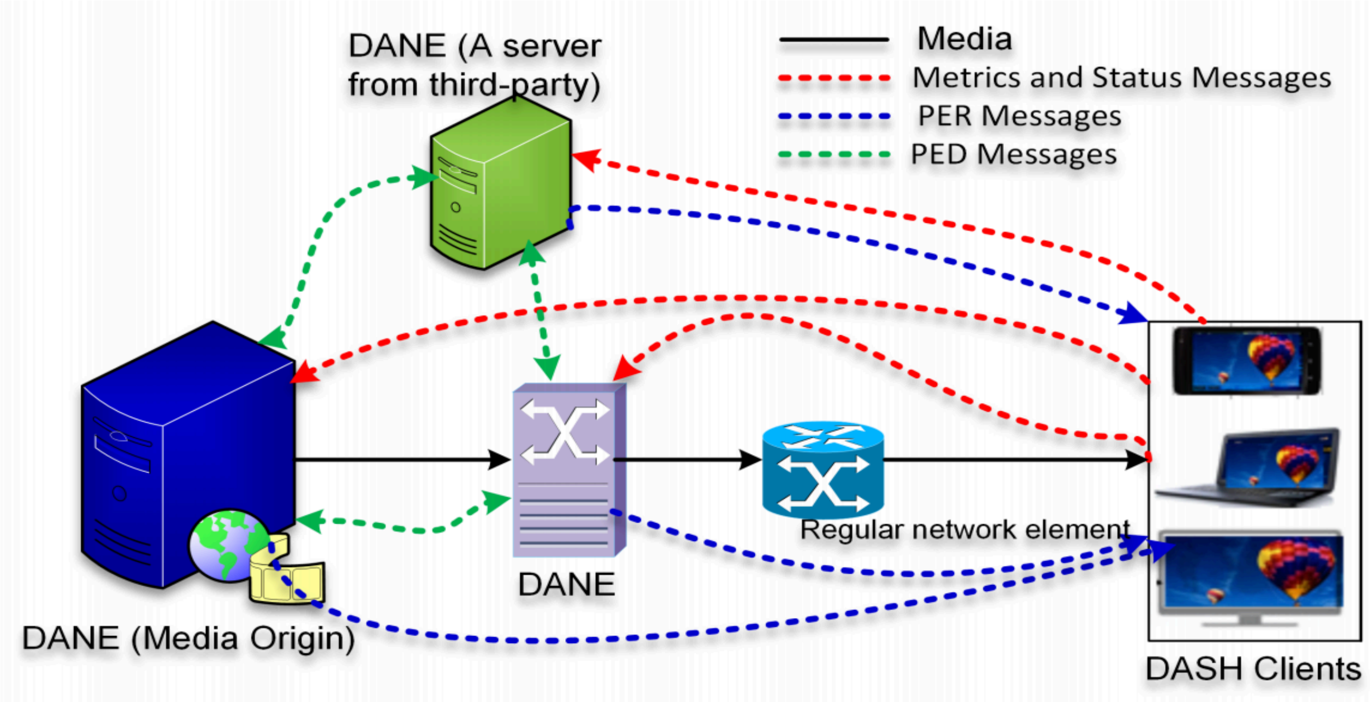
Centralized nodes within the network
⇒ MPEG-SAND standard
(Server and Network Assisted DASH)

# Server And Network Assisted DASH (SAND)

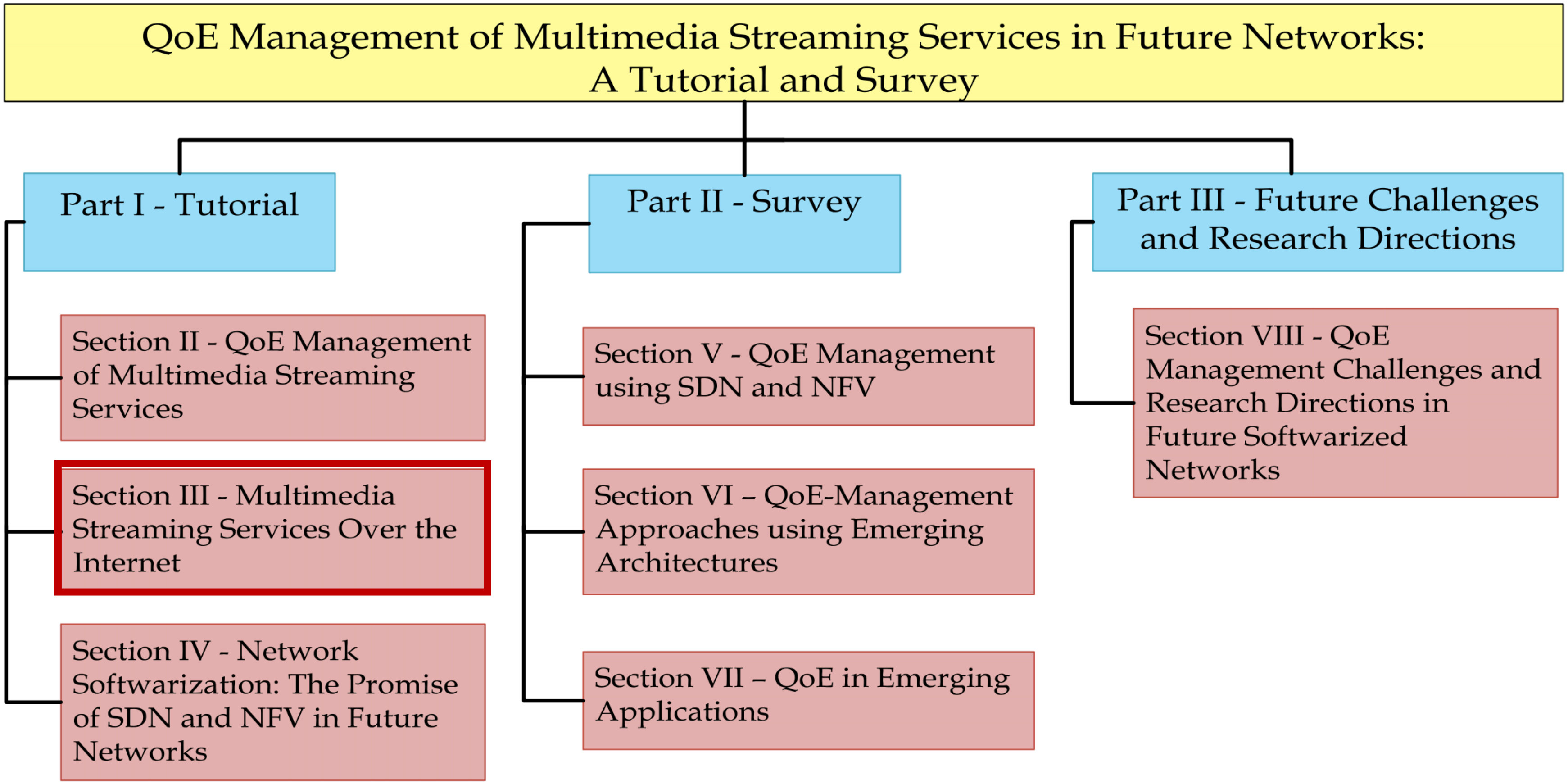
- SAND messages
  - providing information about real-time operational characteristics of networks, servers, proxies, caches, CDNs as well as DASH client's performance
- Designed for
  - content-awareness and QoE-service-awareness through server/network assistance
  - analytics and monitoring of DASH-based services
  - unidirectional/bidirectional, point-to-point/multipoint communication with and without a session (management) between servers/CDNs and DASH clients

# Server And Network Assisted DASH (SAND)

- DASH-Aware Network Elements (DANE)




- SDN can be used to provide a centralized control element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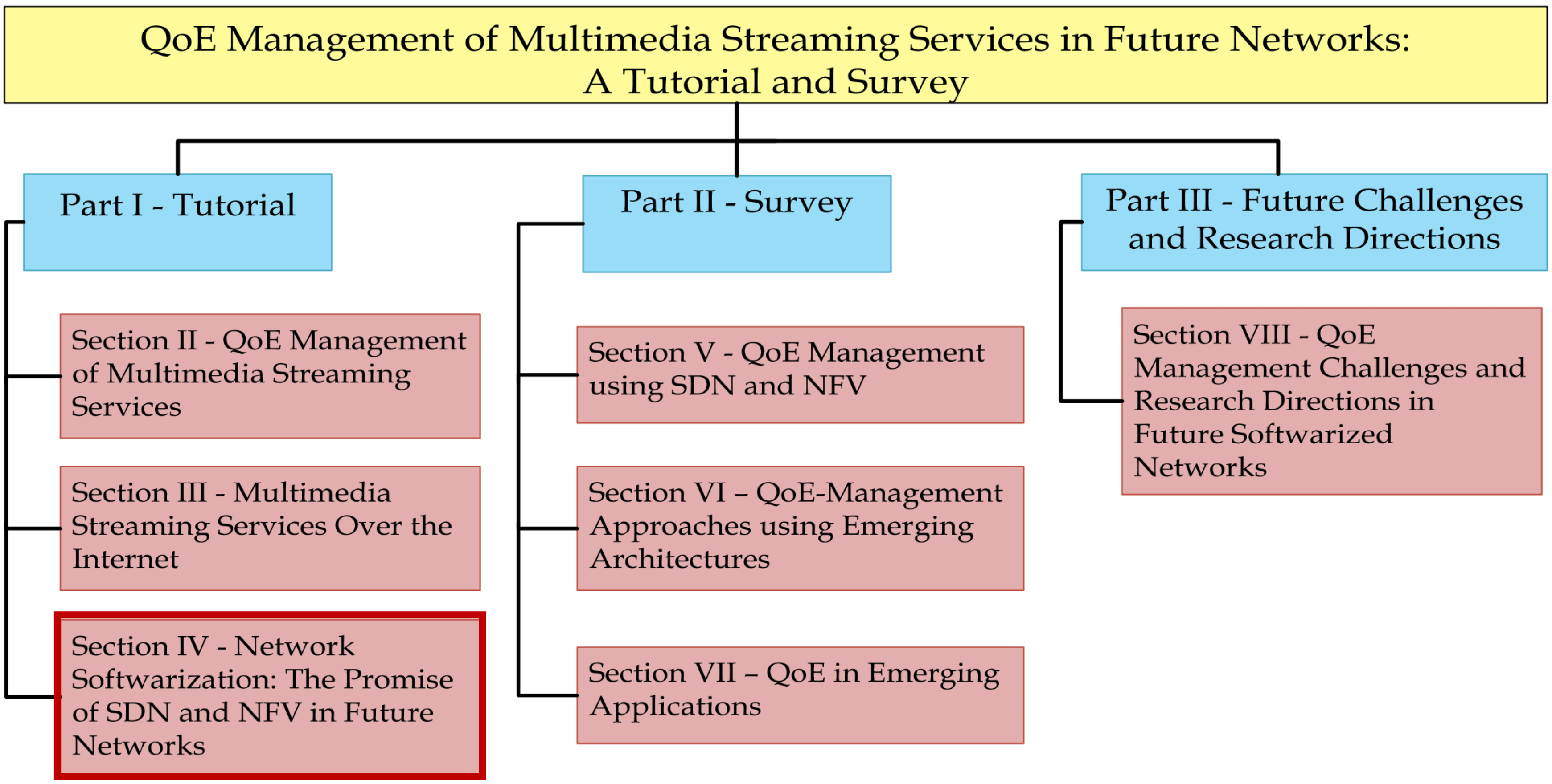
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# Network Softwarization and Virtualization

- Software Defined Networking (SDN)
  - *the physical separation of the network control plane from the forwarding plane, and where a control plane controls several devices*
- Network Function Virtualization (NFV)
  - *the decoupling of physical network equipment from the network functions*

# Network Softwarization and Virtualization

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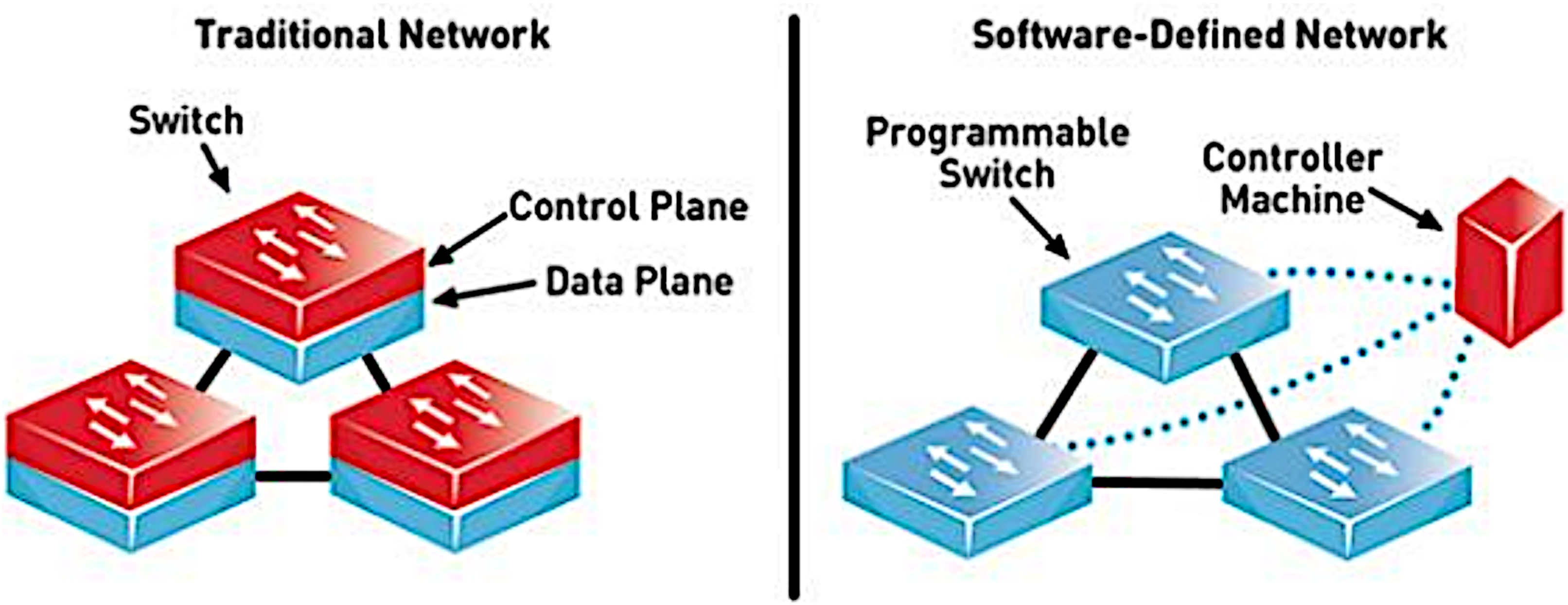
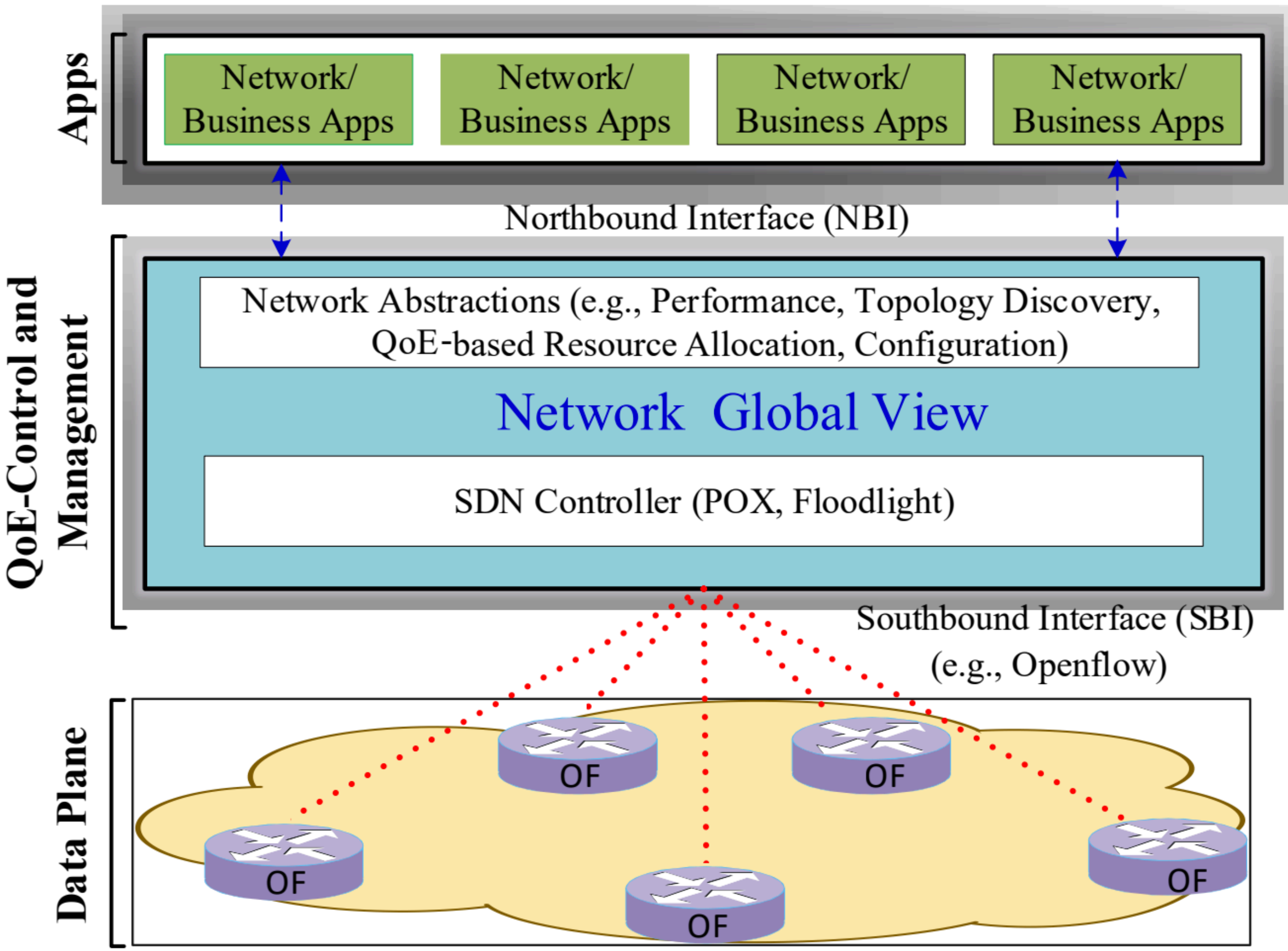
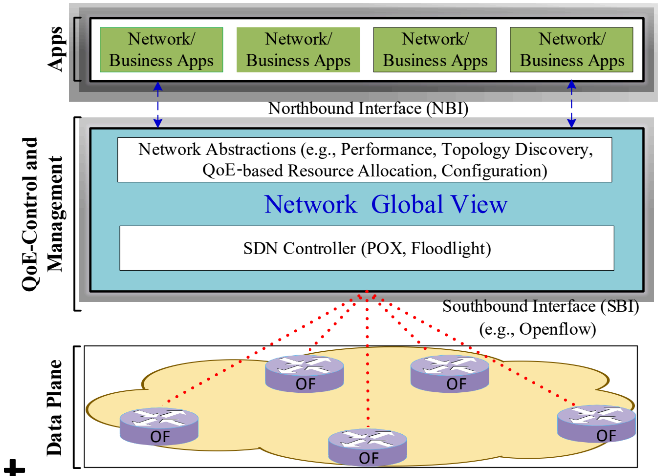


# Main Layers of SDN



# The Advantages of SDN




- Enhanced network programmability
- Centralized control and management
- Increased network flexibility and reliability
- Data flow optimization
- The network control becomes directly programmable using standardized Southbound Interfaces
  - OpFlex [127], FoRCES [128], and OpenFlow [129]
- The forwarding plane of SDN can be implemented on a specific commodity server [130]
  - VMware's NSX platform [131] which consists of a controller and a virtual switch (vSwitch)

# SDN Controller Design and Implementation

- Centralized controller
  - best suited to manage small networks or a single domain
  - may run into scalability and reliability problems
  - e.g., Floodlight [133], Beacon [134], and Ryu NOS [135]
- Distributed controller
  - either a set of elements distributed physically or a centralized cluster of nodes [12]
  - has better scalability and reliability [140]
  - e.g., Hyperflow [136], HP VAN SDN [137], DISCO [138], and ONOS [139]

# SDN Standardization Activities

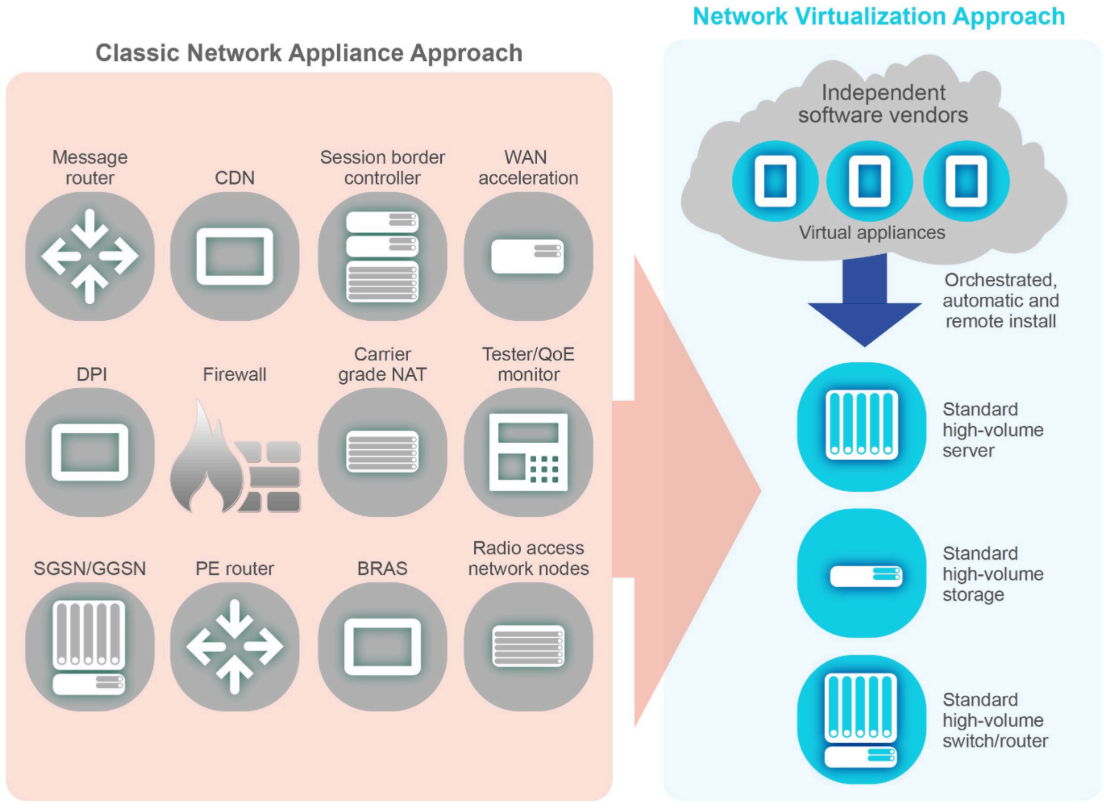
- ONF [126]: SDN architecture, OpenFlow standard
- IETF FORCES [141]: interfaces and protocols
- SDNRG [142]: technical aspects of SDN e.g., solutions for scalability, abstractions, programming languages, etc
- IEEE P1915.1 [143], IEEE P1916.1 [144], and IEEE P1917.1 [145]: requirements, frameworks, and models on the aspects of security, performance, and reliability of SDN
- ITU-T SDN standardization
  - SG11: signaling requirements and protocols of SDN for WAN
  - SG13: use-cases, requirements, and architecture of SDN for NGN
- MEF [146]: SDN technologies to the carrier Ethernet services
- Open source software communities: OpenStack [147], CloudStack [148] and OpenDaylight [149]

# Network Softwarization and Virtualization

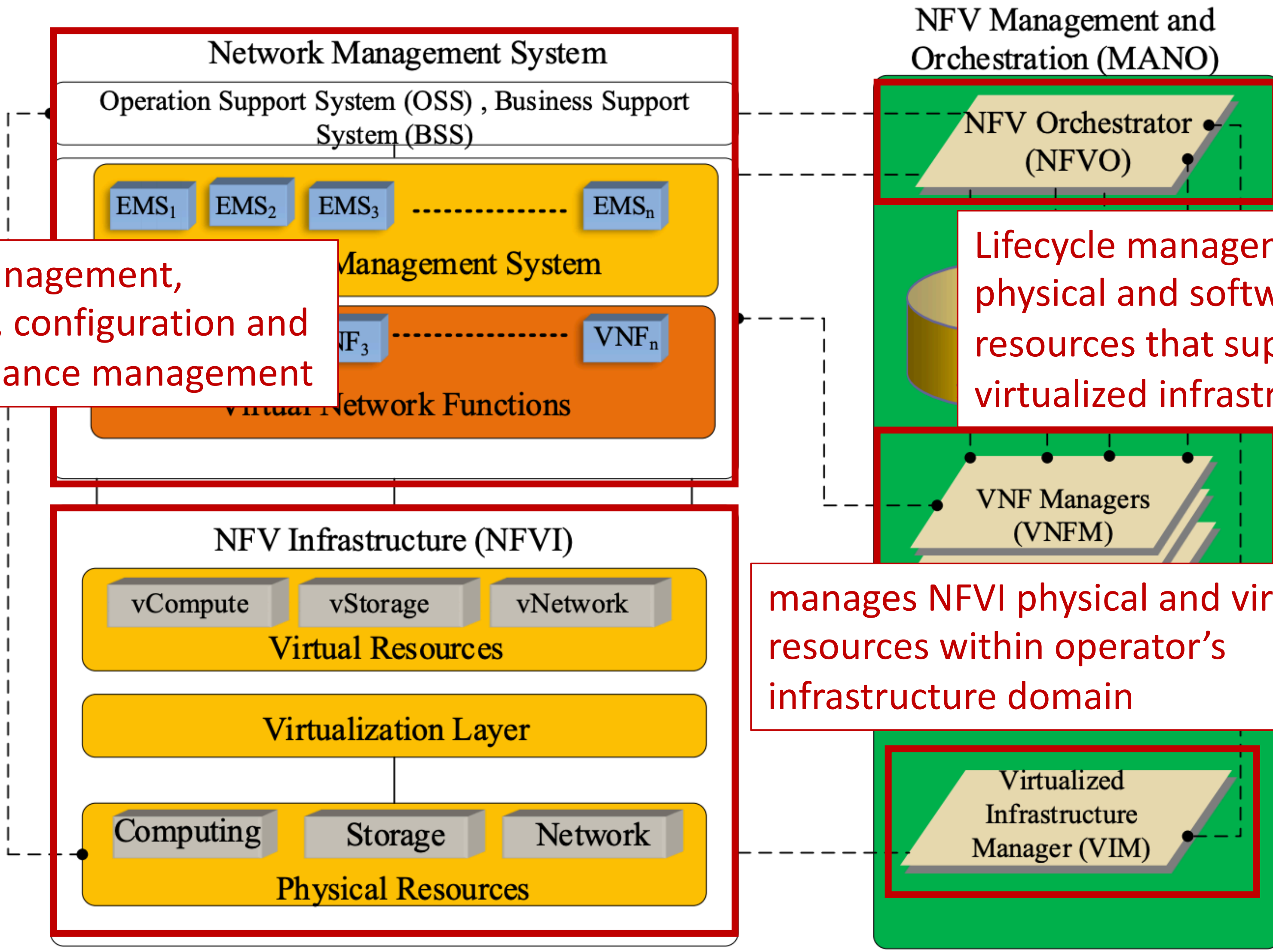
- Software Defined Networking (SDN)
  - *the physical separation of the network control plane from the forwarding plane, and where a control plane controls several devices*
- Network Function Virtualization (NFV)
  - NFV is the decoupling of physical network equipment from the network functions

# Network Function Virtualization (NFV)

- Decoupling software from hardware platform
- Providing greater flexibility for NFs deployment
- Enabling dynamic network operation and service provisioning



# Network Function Virtualization (NFV)




fault management, security, configuration and performance management

Lifecycle management of physical and software resources that support the virtualized infrastructure

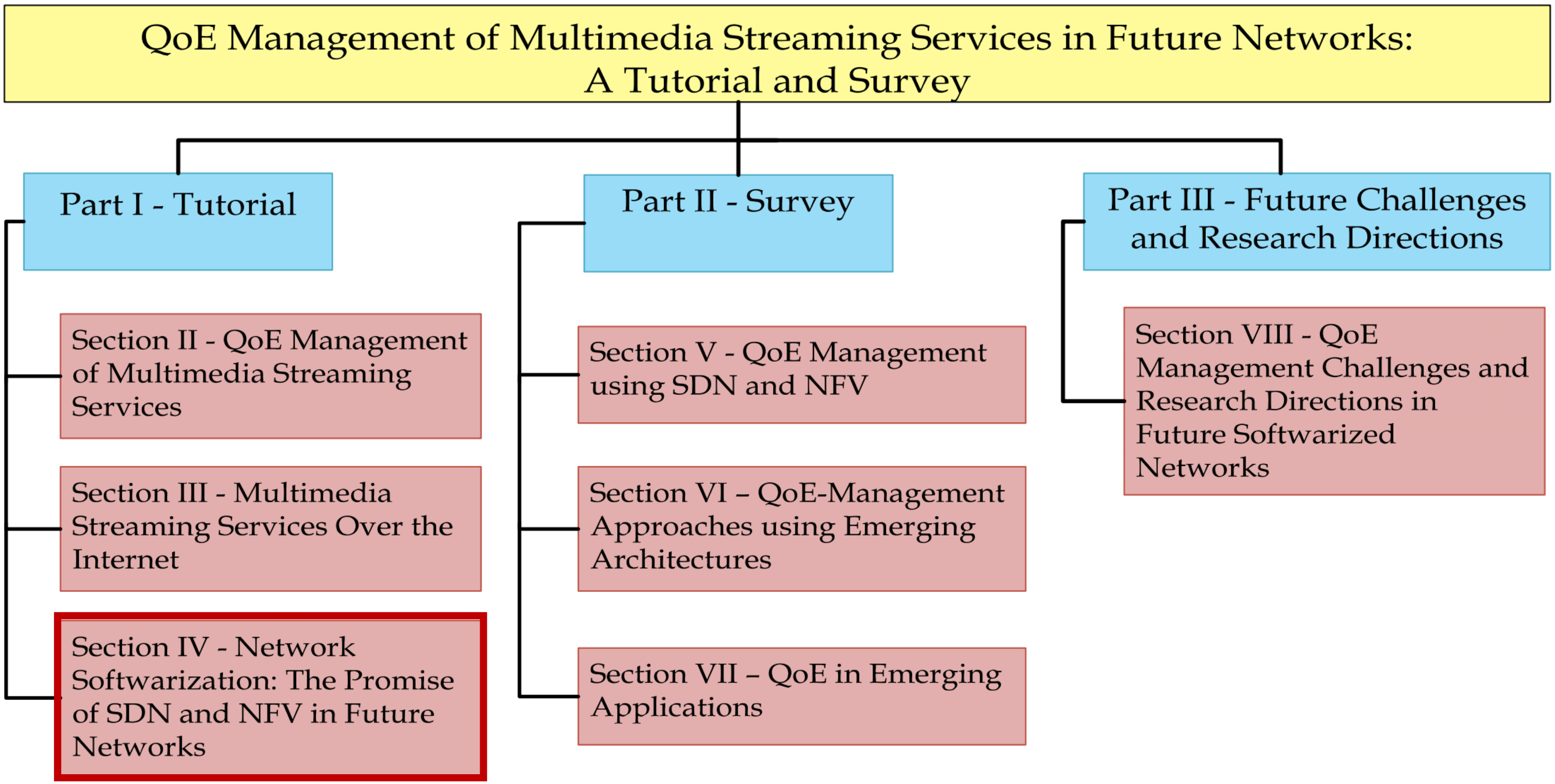
manages NFVI physical and virtual resources within operator’s infrastructure domain

# NFV Use Cases, Application Scenarios and Implementation

- Defined by the ETSI [156]
- Other use cases:
  - pertaining to QoE-based multipath routing [157]
  - virtual function implementation for broadband remote access server [158]
  - deep packet inspection [159]
  - radio access network (RAN) [160]–[162]
  - customer premises equipment (CPE) [163]–[165]
  - evolved packet core (EPC) [166]–[168]
  - QoE monitoring through virtualized probes [60]
  - CloudNFV [169], Huawei NFV Open Lab [170], HP OpenNFV [171], Intel ONP [172], Cisco Open Network Strategy [173], Alcatel-Lucent CloudBand [174], [175], Broadcom Open NFV [176] and F5 DAS [13]

# NFV Standardization Activities

- NFVRG [177]: new virtualized architectures with capabilities to provide support for NFs
- IETF SFC WG [178]: SFC architectural building blocks
- ETSI NFV ISG [179]:
  - use cases for NFV requirements, architectural framework [154], [153]
  - interfaces and abstractions for NFVI, NFV security [180]
  - performance and resiliency [181]
- ATIS NFV [182]: use cases for collaboration among service providers
- Broadband Forum [183]: Multi-Service Broadband Network (MSBN)
- OVF, ITU-T SG13: functional requirements and architecture of the network virtualization for NGN
- Implementation projects: OPNFV [185], ZOOM [186], OpenMANO [187], and UNIFY [188], [189]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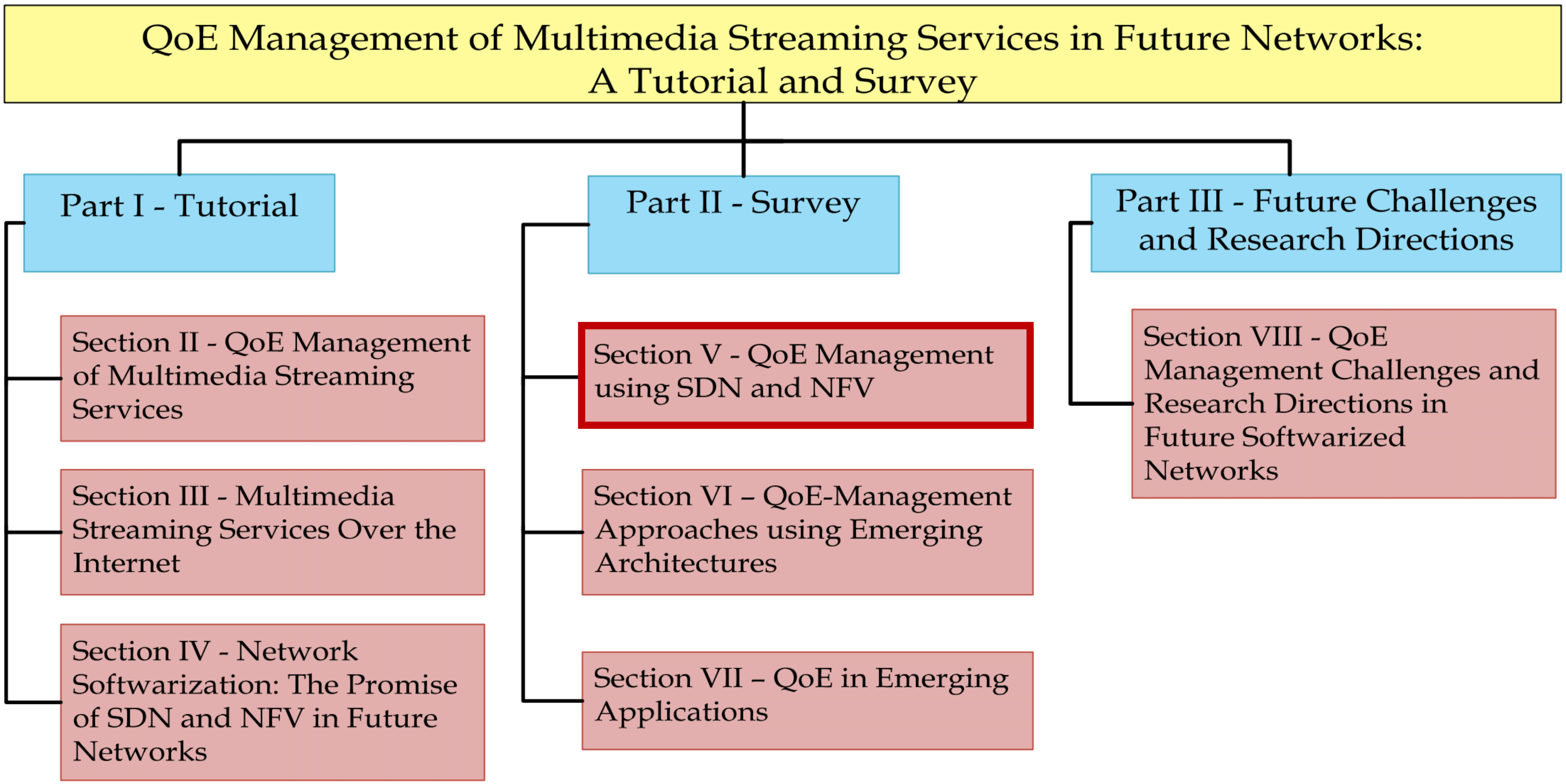
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# QoE Management using SDN and NFV

| Strategy | Major contributions | Contribution/Objectives/Functionality |
| --- | --- | --- |
| Server and Network-Based Optimization | Bandwidth reservation [107], [196], [200] or bitrate guidance [7], [197], [108], [245] video stream prioritization [246], CDN orchestration and caching optimization [247], server-assisted delivery [110] | Maximizes the end users' QoE through the best path calculations for each service flow, optimal bitrates computation for the clients so as to obtain QoE-fairness in the delivered video, Optimizing the QoE by assigning a different priority to a video stream depending on the requested quality |
| QoE-Fairness and Personalized QoE-centric control | [193], [7], [205], [198], [106], [206], [207], [199], [19] | Efficient network resources allocation to ensure that the maximum users' QoE fairness is achieved. The basic idea is to avoid quality instability, unfair bandwidth sharing and network resource underutilization among DASH competing clients sharing the same bottleneck network link. |
| QoE-centric Re-routing Mechanisms | [209], [208], [213], [215], [248], [249] | Maximizes the end users' QoE through the best path calculations for each service flow. That way, the video is streamed over links with low-latency, high-throughput which increases the achieved video quality. |
| QoE-aware Cross-layer Optimization | [73], [250]–[252] | To utilize network resources efficiently and optimize the end-users' QoE through a joint cooperation between layers and coordination of their actions. In such a design, the QoE requirements can be specified at the application layer and controlled at the network layer using SDN controllers [21], [253] |
| Transport Level Optimizations | TCP/MPTCP solutions for HAS [157], [232], [233], [235] | To facilitate efficient multipath-routing and speed up the transfer of large amount of multimedia applications between end-points while guaranteeing the end users' QoE in SDN-based networks. MPTCP provides load balancing, reliable communication and better network resources utilization that leads to higher network throughput and the end-users' QoE [226], [237]. |

# QoE Management using SDN and NFV

e.g., SAND

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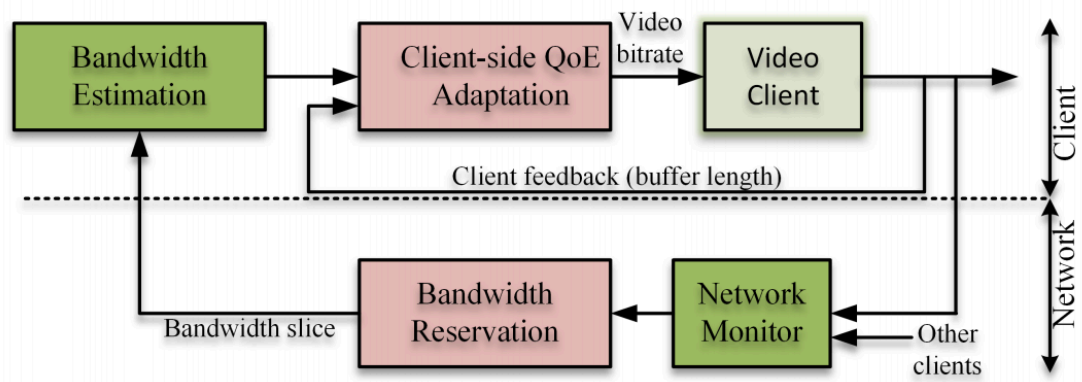
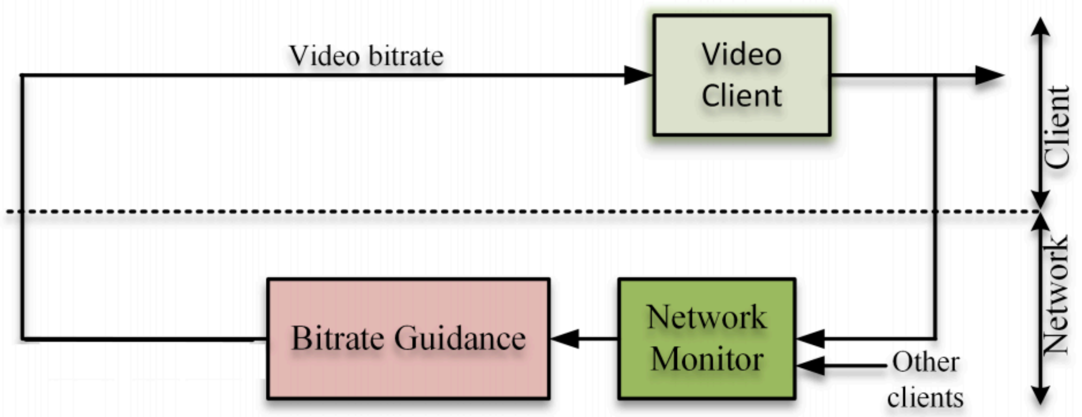
# Server and Network-based Optimization

- Bandwidth Reservation [107,196,200]




- Bitrate Guidance [7,197,108,245]



# QoE Management using SDN and NFV

| Strategy | Major contributions | Contribution/Objectives/Functionality |
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| Server and Network-Based Optimization | Bandwidth reservation [107], [196], [200] or bitrate guidance [7], [197], [108], [245] video stream prioritization [246], CDN orchestration and caching optimization [247], server-assisted delivery [110] | Maximizes the end users' QoE through the best path calculations for each service flow, optimal bitrates computation for the clients so as to obtain QoE-fairness in the delivered video, Optimizing the QoE by assigning a different priority to a video stream depending on the requested quality |
| QoE-Fairness and Personalized QoE-centric control | [193], [7], [205], [198], [106], [206], [207], [199], [19] | Efficient network resources allocation to ensure that the maximum users' QoE fairness is achieved. The basic idea is to avoid quality instability, unfair bandwidth sharing and network resource underutilization among DASH competing clients sharing the same bottleneck network link. |
| QoE-centric Re-routing Mechanisms | [209], [208], [213], [215], [248], [249] | Maximizes the end users' QoE through the best path calculations for each service flow. That way, the video is streamed over links with low-latency, high-throughput which increases the achieved video quality. |
| QoE-aware Cross-layer Optimization | [73], [250]–[252] | To utilize network resources efficiently and optimize the end-users' QoE through a joint cooperation between layers and coordination of their actions. In such a design, the QoE requirements can be specified at the application layer and controlled at the network layer using SDN controllers [21], [253] |
| Transport Level Optimizations | TCP/MPTCP solutions for HAS [157], [232], [233], [235] | To facilitate efficient multipath-routing and speed up the transfer of large amount of multimedia applications between end-points while guaranteeing the end users' QoE in SDN-based networks. MPTCP provides load balancing, reliable communication and better network resources utilization that leads to higher network throughput and the end-users' QoE [226], [237]. |

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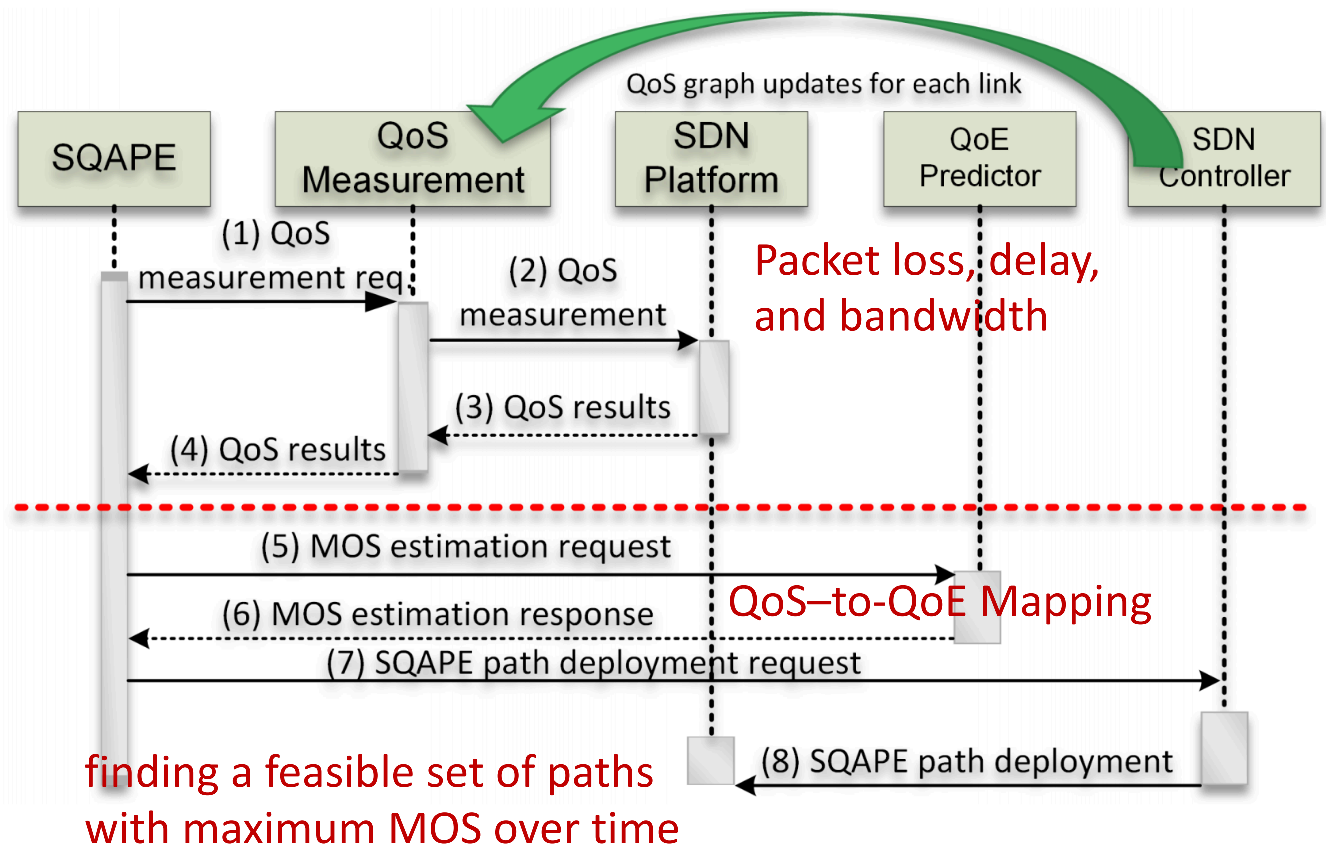
# QoE-Centric Re-routing Mechanism

- Scalable QoE-aware path selection (SQAPE) in large-scale SDN-based networks [217]



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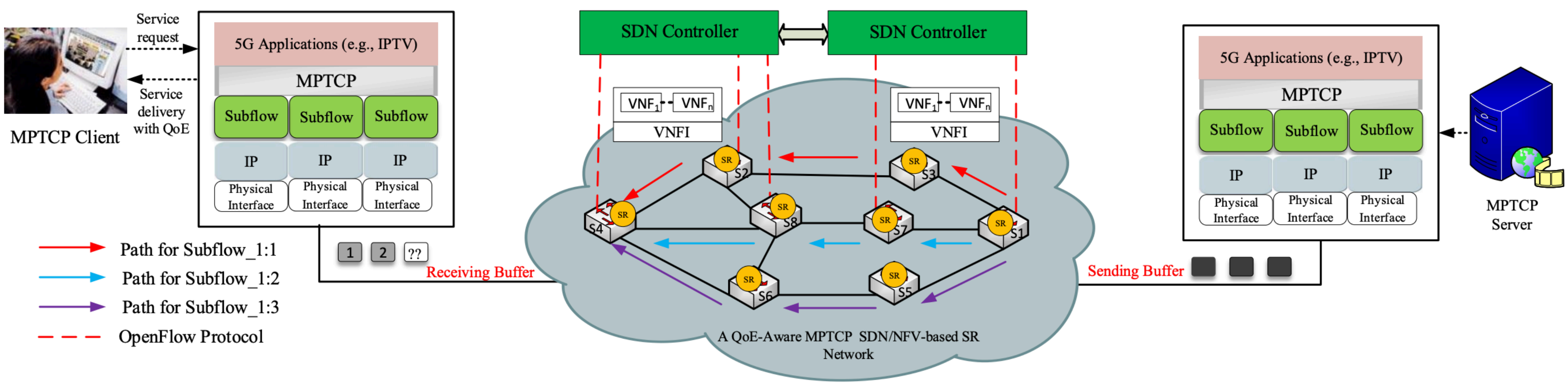
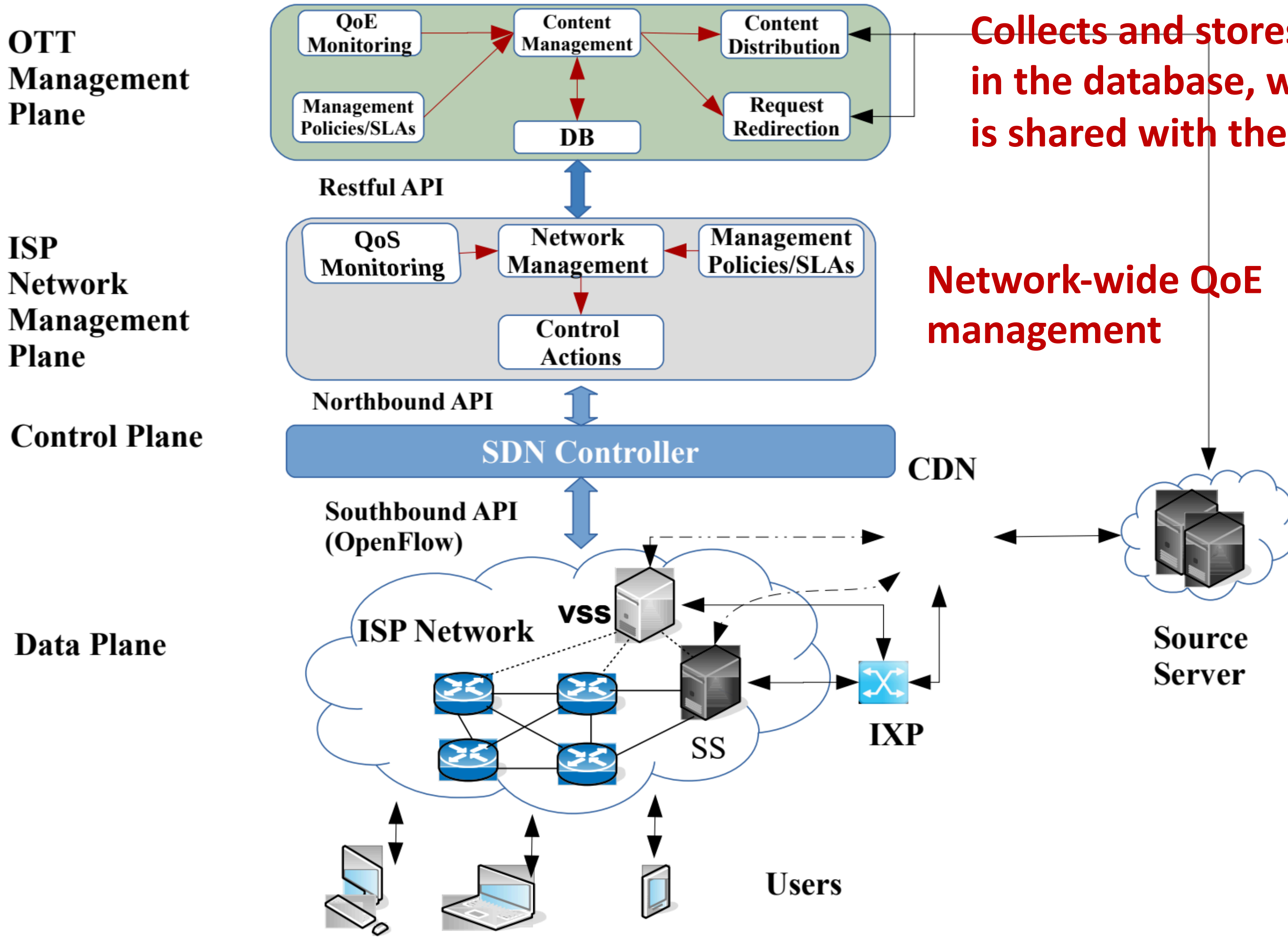
# MPTCP in SDN/NFV-based Networks

- Creating multiple subflows and distributing them over multiple disjoint paths in the network

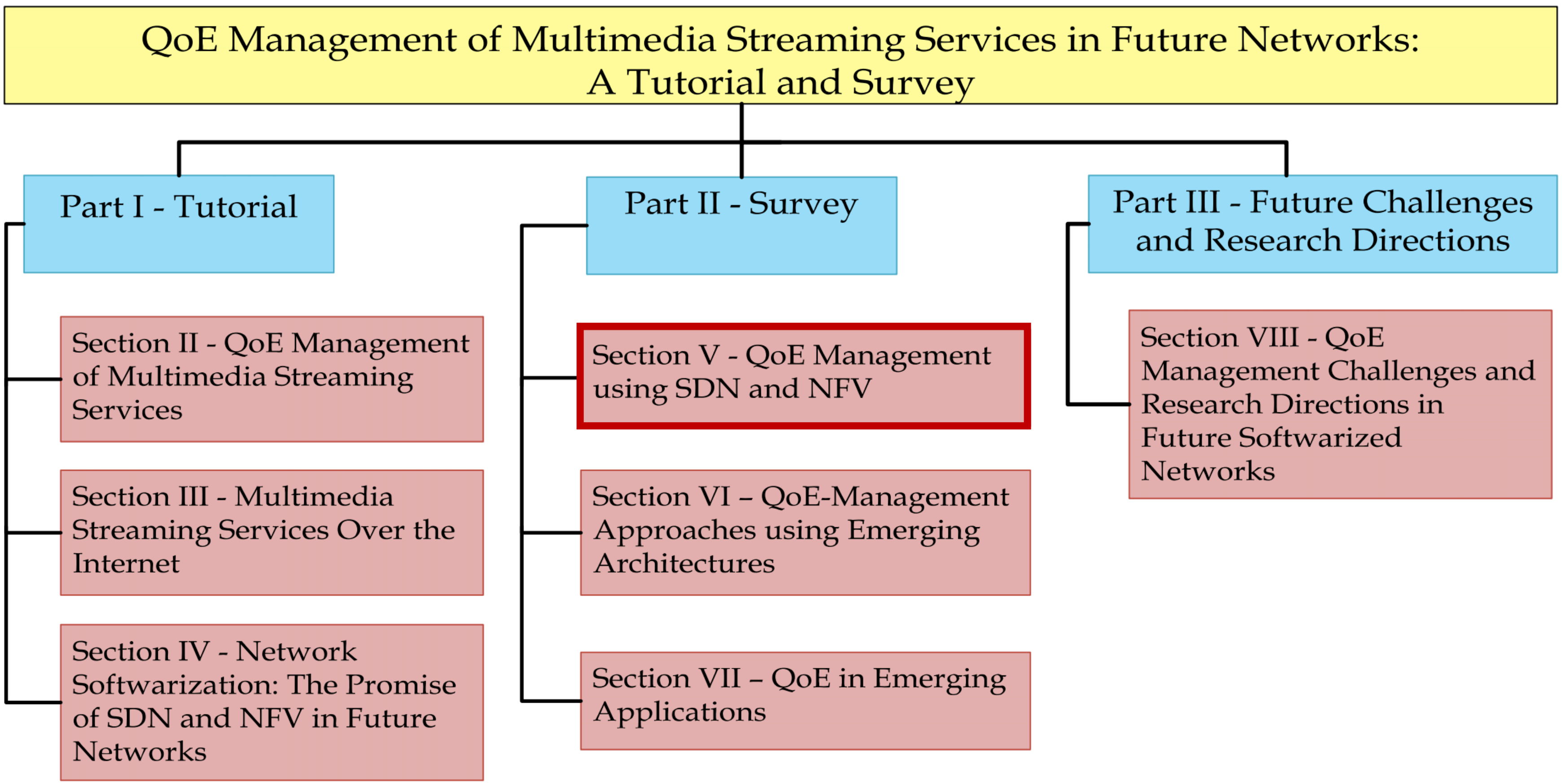


# Collaborative Service QoE Management by OTTP and ISP through SDN and NFV




**Collects and stores KQIs in the database, which is shared with the ISP**

**Network-wide QoE management**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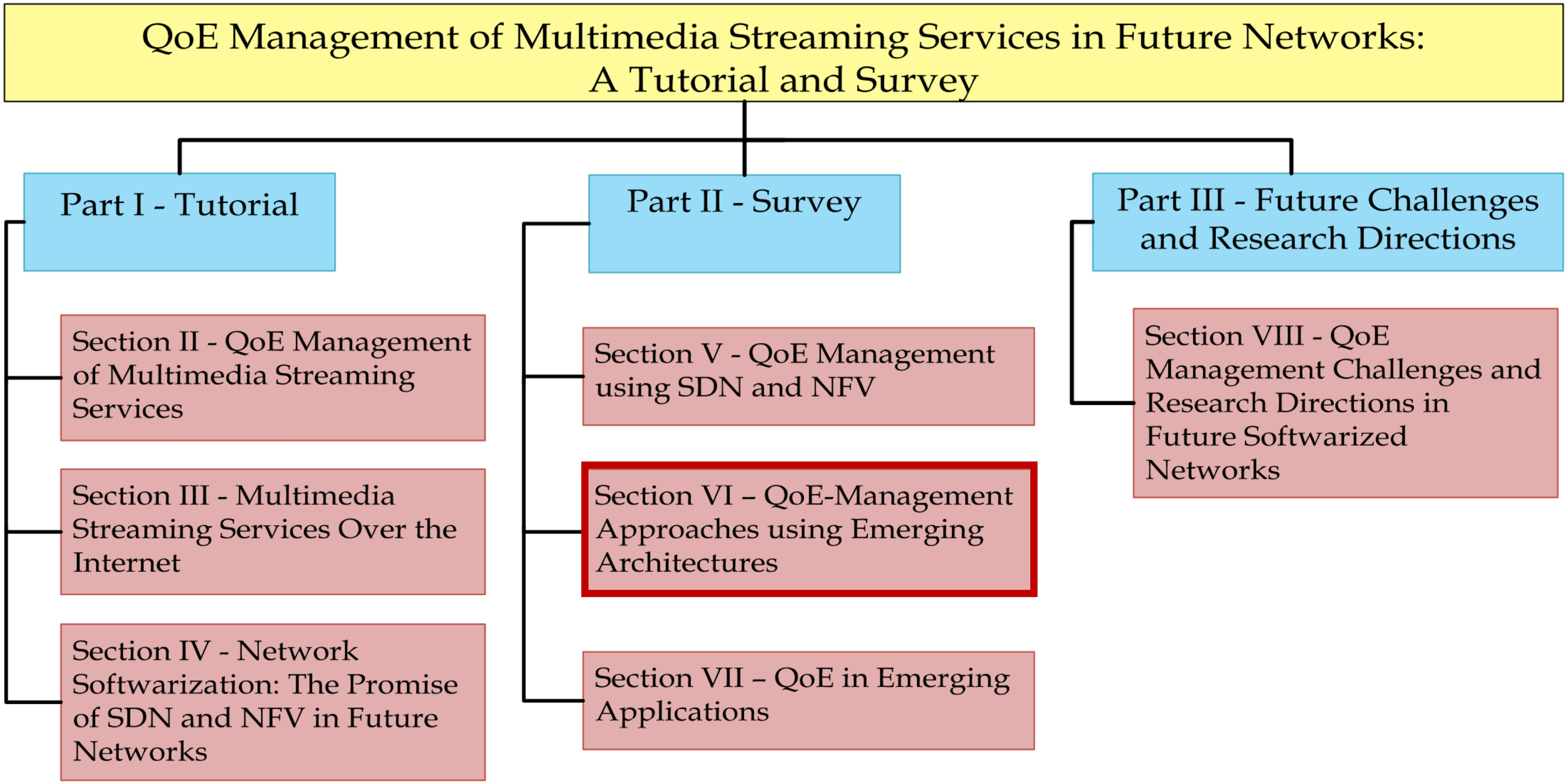
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| QoE-aware/driven Adaptive Streaming over MEC | QoE-aware software driven multi-access edge service management [35], [266]–[268], [271], [273], [275], [303] | Decrease the content delivery latency and improve the utilization of the network resources. Enable QoE monitoring and video quality adaptation using the real-time knowledge of UEs and network. |
| QoE-aware Adaptive Streaming over Cloud/Fog computing | QoE-based resource management [274], [276], [277], [304]–[306], QoE optimization with energy efficiency [285] | Perform QoS/QoE-aware orchestration of resources by scheduling flows between services. Some of the proposals such as in [284] can enable service providers to predict the QoE of DASH-supported video streaming using fog nodes. |
| QoE-driven/aware Management using ICN | [279], [281], QoE-driven content caching and adaptation scheme over MEC-enabled ICN [303] | Performing prefetching of video streams that enables ICN to compute the link resources availability and makes scheduling of data units dissemination called "chunks" to edge caches according to end-users' requests [307] or video prefetching at the network edge in order to achieve the users' QoE [302] |

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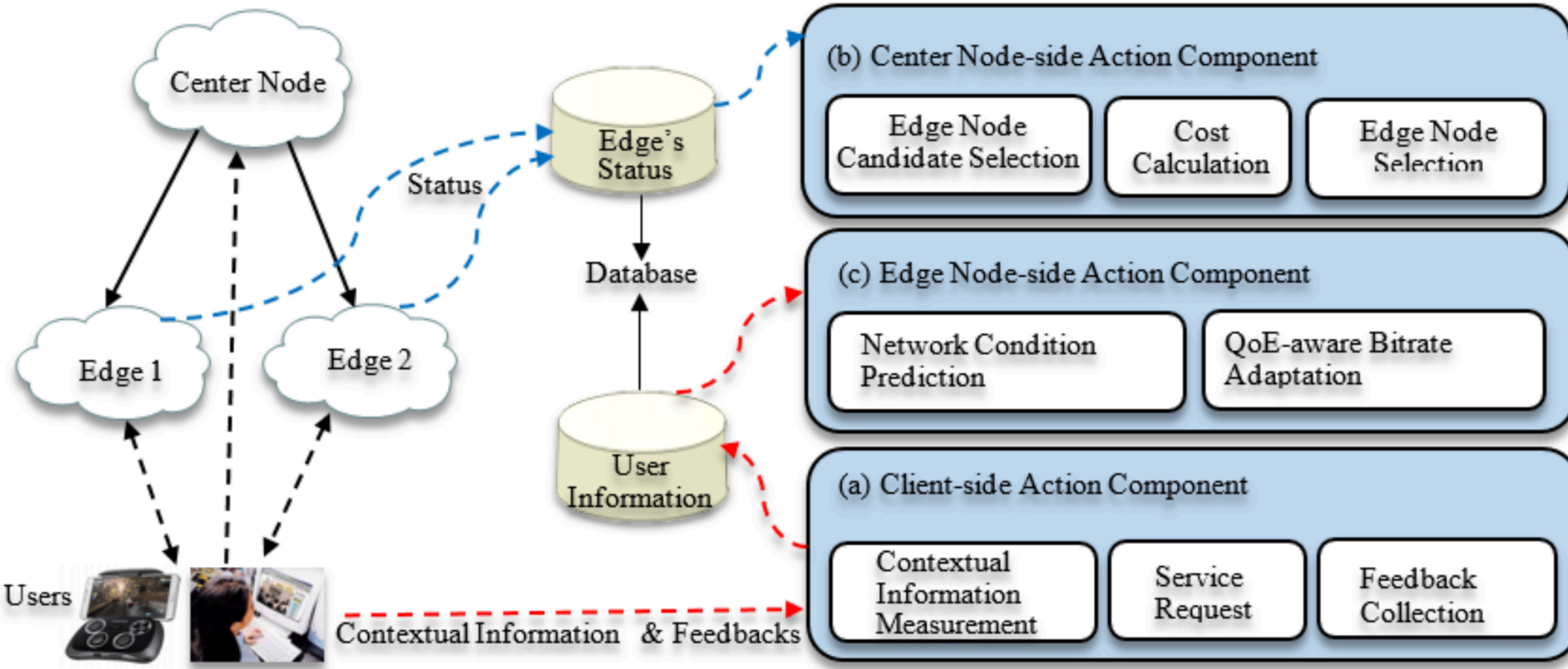
# QoE-aware Control Plane for Adaptive Streaming service in MEC [275]

prevent end-user clients' to access video contents from the center node simultaneously




play status, locations and activities

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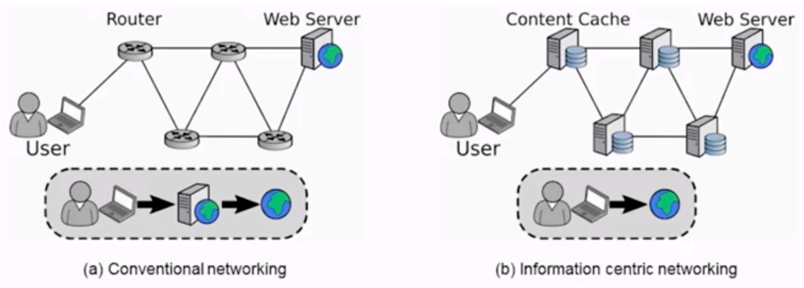

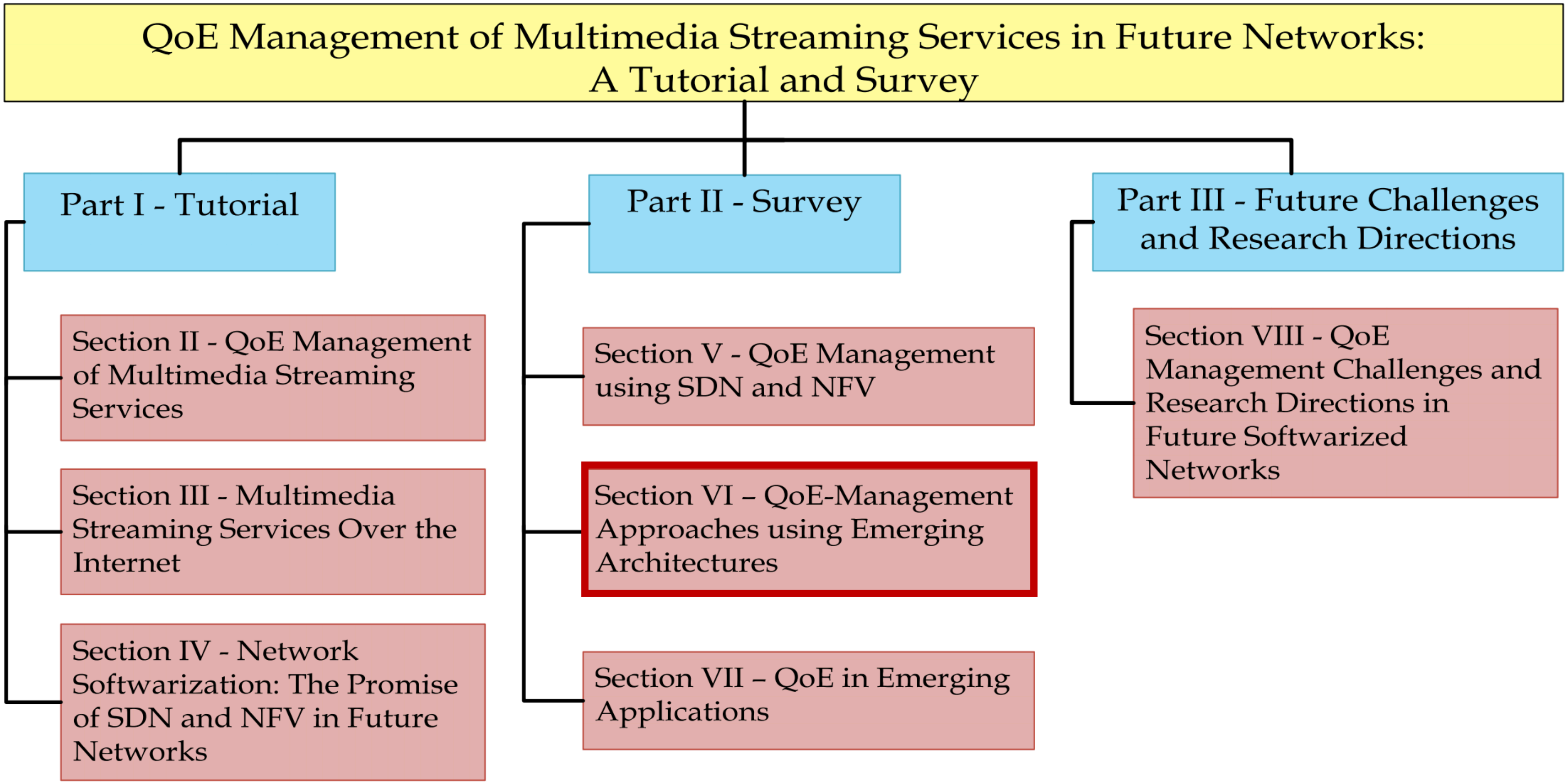
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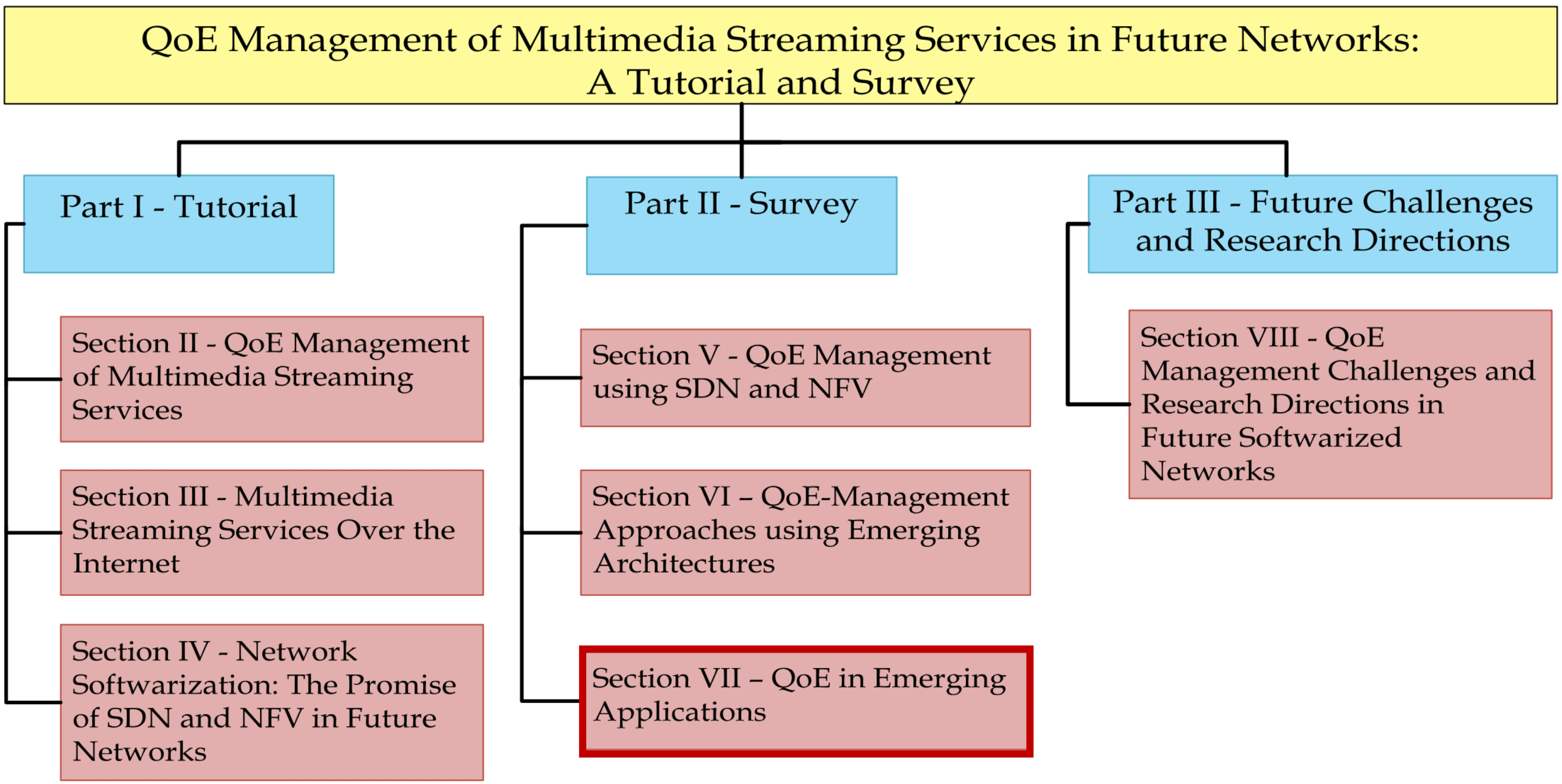
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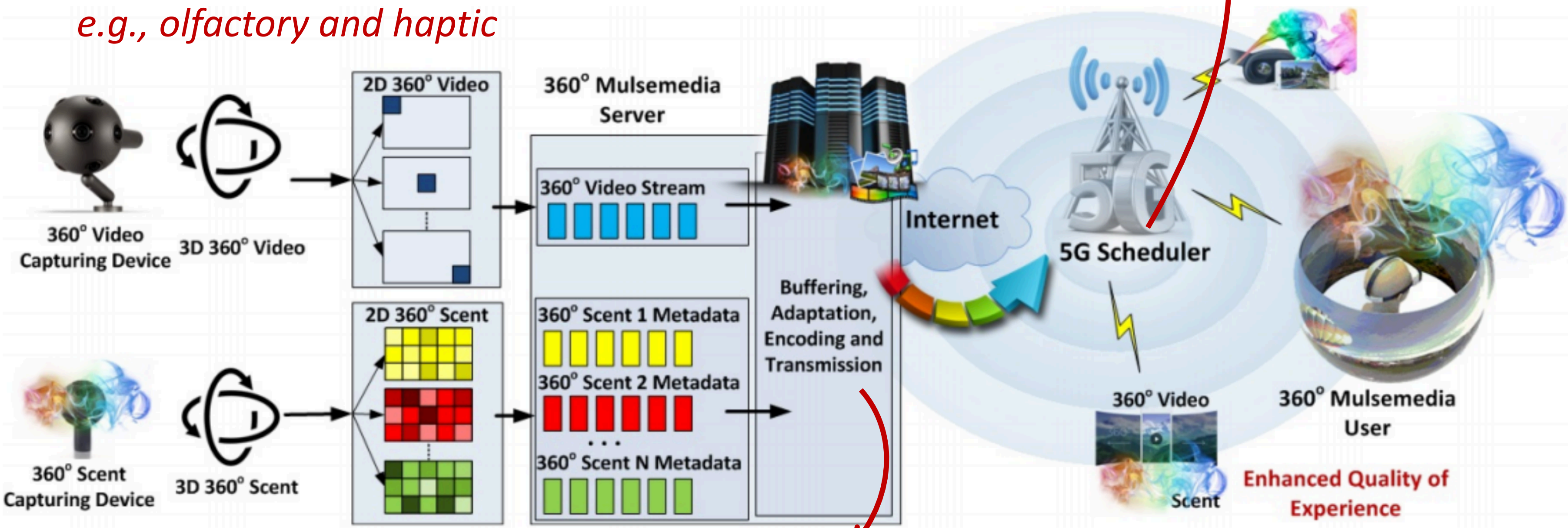
# QoE in Emerging Applications

- AR applications [289-291]
- Mulsemedia services [292-299,320]

  *e.g., olfactory and haptic*

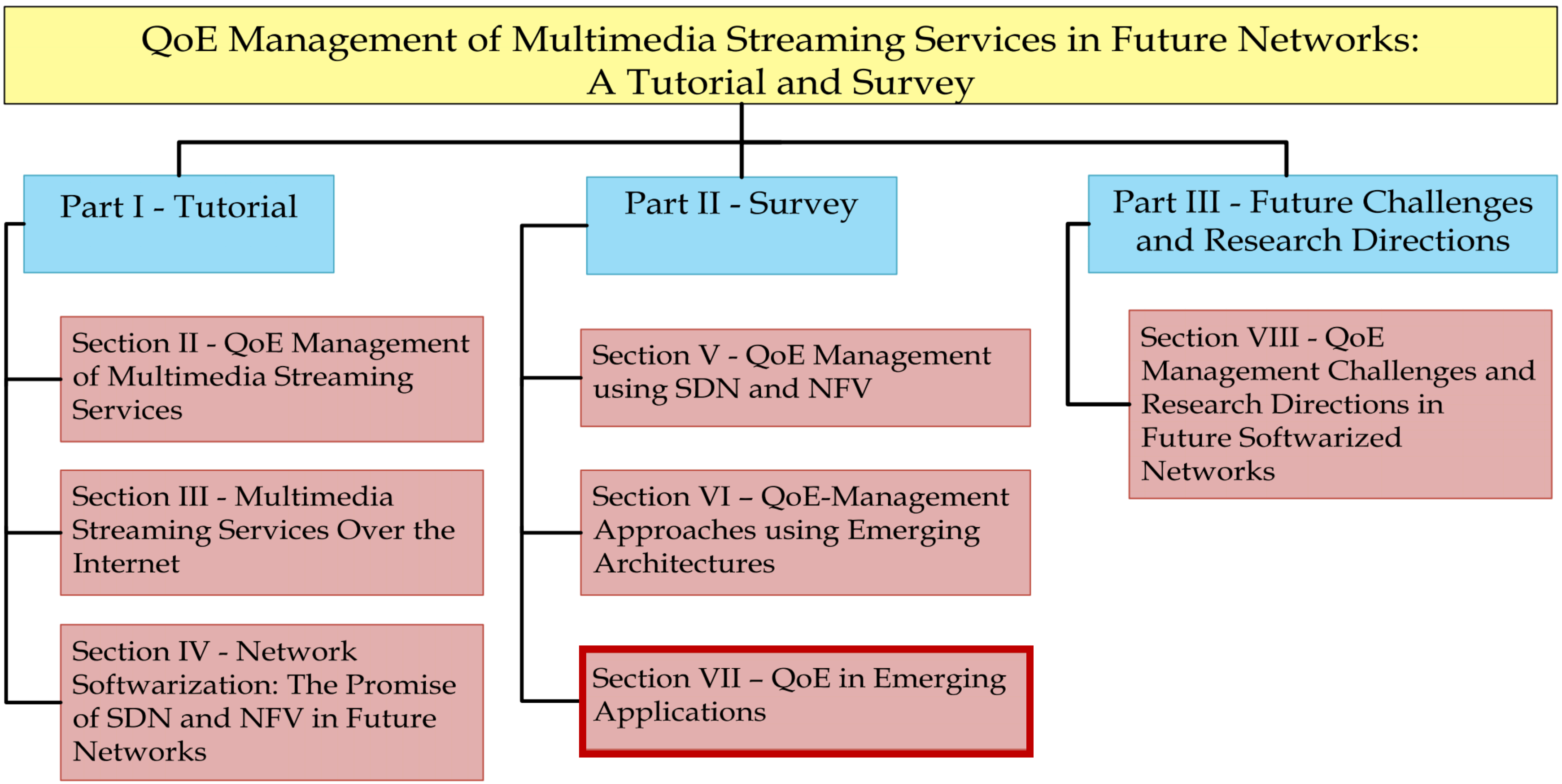
the number of 360◦ mulsemedia users, mobility, positioning and channel conditions




360◦ olfactory objects mapping, 360◦ media objects synchronization, buffering, adaptation encoding and transmission

# QoE in Emerging Applications

- QoE in Cloud Gaming Video Streaming Applications
  - designing the SDN controller to provide lower latency and higher QoE [326-327]
  - ITU-T recommendations [328-329] for subjective and objective quality assessment of video gaming streaming services
  - quality evaluation during gaming [330]
  - gaming video datasets [331]
  - evaluation of existing metrics [332]–[335]
  - development of new no-reference metrics and models [46], [336], [337] for gaming content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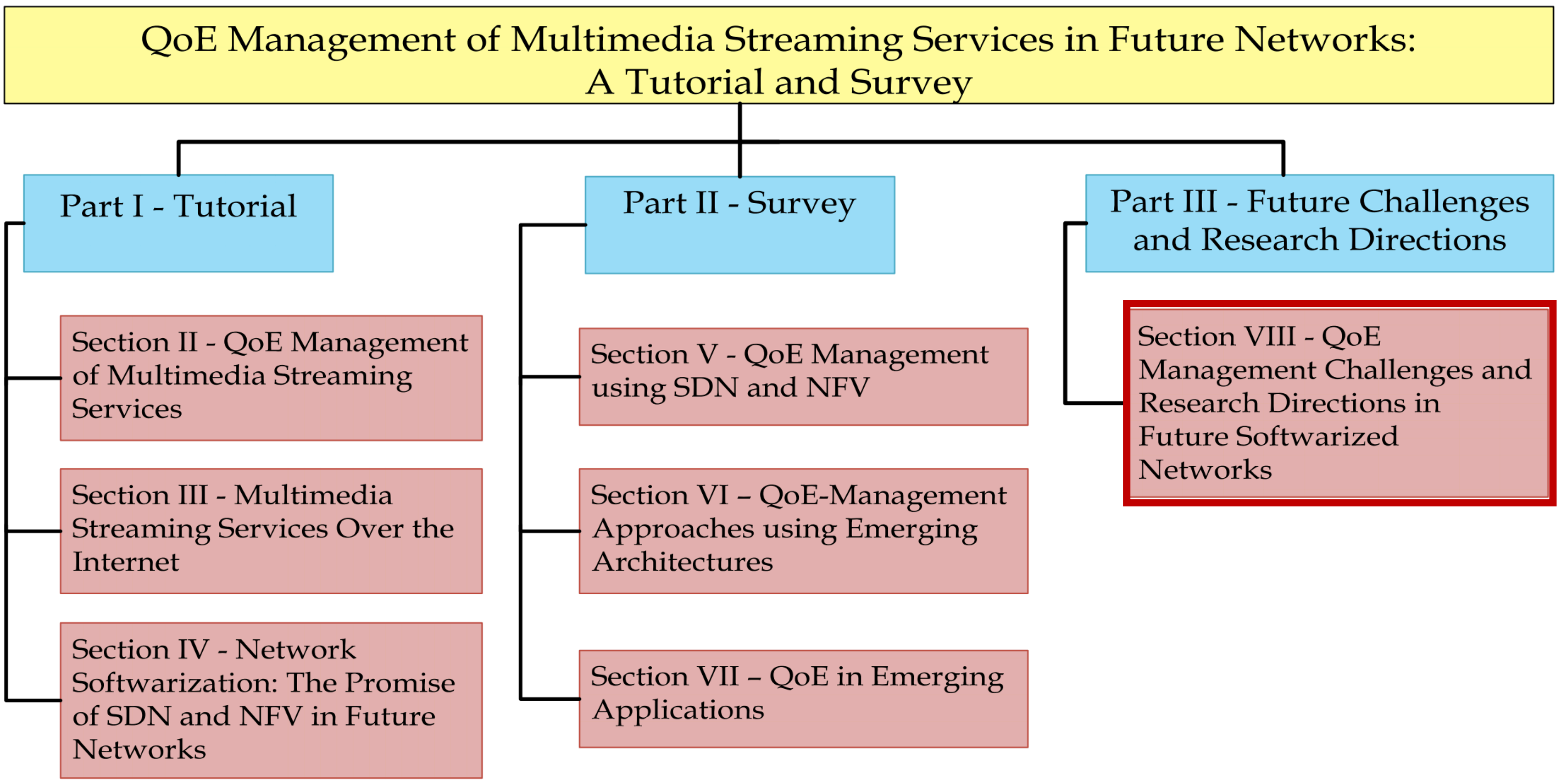
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# QoE Management Challenges and Research Directions in Future Softwarized Networks

| Challenge | Current Contributions | Research Opportunities |
|---|---|---|
| OTTP and ISP Collaboration | [2], [112], [116], [240], [242] [241], [4], [243], [244] | The collaborative QoE-aware service management solutions including the reference architecture, optimization algorithms for the service management and business models. |
| Emerging Multimedia Applications | [31], [287]–[289], [321], [292], [293], [336], [332], [333], [335], [341] | Mechanisms for ensuring the QoE for VR/AR, Mulsemedia, Video gaming and light fie… have thr… user, an… ext in wh… ers is ins… work, ap… alized mo… |
| Management and Orchestration | [7], [60], [185], [107], [342]–[352], [19]–[21], [246] | Th… ontext of… livery ser… |
| HTTP Adaptive Streaming over MPTCP/QUIC, Immersive Video Streaming | [157], [226], [232]–[235], [237], [353], [354] | M… over softwarized 5G networks is needed. For immersive video streaming, viewport-dependent solutions for VR streaming in future communication systems have to be investigated more. |
| Video Encoding | [355]–[357] | Many current video encoding strategies are focusing on improving existing codecs or develop newer encoders to achieve higher compression efficiency especially for new contents (e.g., HDR, AR/VR and video gaming), so as to reduce the required transmission bandwidth. However, with the arrival of IoT and M2M communications in 5G networks, it is imperative for the industry and academia to come up with newer solutions catering to the changing requirements of such applications (such as low-delay, low power and low complexity encoders). |

- Interfaces for the information exchange, e.g., using cloud databases [4]
- SLAs/ELAs and business agreements among the providers for the service management policies

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- Context
- QoE personalized models

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| Management and Orchestration | [7], [60], [185], [107], [342]–[352], [19]–[21], [246] | The management and orchestration of both SDN and NFV resources in the context of FNs. QoE-aware/driven softwarized management schemes for multimedia delivery services in FNs are not covered yet. |
| HTTP Adaptive Streaming over MPTCP/QUIC, Immersive Video Streaming | [157], [226], [232]–[235], [237 [353], [354] | More investigation on the impact of MPTCP/QUIC and SR on adaptive streaming over |
| Video Encoding | [355]–[357] | |

- Existing projects are focusing on novel architectures that provide the needed flexibility and programmable networks using SDN/NFV
- QoE-aware/driven management schemes for multimedia delivery services over future softwarized infrastructures are not covered yet

# QoE Management Challenges and Research Directions in Future Softwarized Networks

| Challenge | Current Contributions | Research Opportunities |
|---|---|---|
| OTTP and ISP Collaboration | [2], [112], [116], [240], [242] [241], [4], [243], [244] | The collaborative QoE-aware service management solutions including the reference architecture, optimization algorithms for the service management and business models. |
| Emerging Multimedia Applications | [31], [287]–[289], [321], [292], [293], [336], [332], [333], [335], [341] | Mechanisms for ensuring the QoE for VR/AR, Mulsemedia, Video gaming and light field display. The current QoE models for delivery of adaptive video streams have three limitations: (1) they are developed to capture the behavior of the "average" user, and hence some of them are not personalized, (2) they do not consider the context in which the streaming session takes place, and (3) only the QoE model of the users is inserted into the control loop, but not the user herself [31]. Therefore, using the network, application and user-level parameters could potentially allow creating QoE personalized models of emerging multimedia services. |
| Management and Orchestration | [7], [60], [185], [107], [342]–[352], [19]–[21], [246] | The management and orchestration of both SDN and NFV resources in the context of FNs. QoE-aware/driven softwarized management schemes for multimedia delivery services in FNs are not covered yet. |
| HTTP Adaptive Streaming over MPTCP/QUIC, Immersive Video Streaming | [157], [226], [232]–[235], [237], [353], [354] | More investigation on the impact of MPTCP/QUIC and SR on adaptive streaming over softwarized 5G networks is needed. For immersive video streaming, viewport-dependent solutions for VR streaming in future communication systems have to be investigated more. |
| Video Encoding | [355]–[357] | [illegible] codecs [illegible] ally for [illegible] required [illegible] ications [illegible] h newer [illegible] w-delay, |

- Investigation on emerging protocols, e.g., MPTCP and QUIC
- Viewport-adaptive streaming

# QoE Management Challenges and Research Directions in Future Softwarized Networks

| Challenge | Current Contributions | Research Opportunities |
| --- | --- | --- |
| OTTP and ISP Collaboration | [2], [112], [116], [240], [242] [241], [4], [243], [244] | The collaborative QoE-aware service management solutions including the reference architecture, optimization algorithms for the service management and business models. |
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| Management and Orchestration | [7], [60], [185], [107], [342]–[352], [19]–[21], [246] | [illegible] context [illegible] delivery |
| HTTP Adaptive Streaming over MPTCP/QUIC, Immersive Video Streaming | [157], [226], [232]–[235], [237], [353], [354] | [illegible] ing over [illegible] pendent [illegible] stigated more. |
| Video Encoding | [355]–[357] | Many current video encoding strategies are focusing on improving existing codecs or develop newer encoders to achieve higher compression efficiency especially for new contents (e.g., HDR, AR/VR and video gaming), so as to reduce the required transmission bandwidth. However, with the arrival of IoT and M2M communications in 5G networks, it is imperative for the industry and academia to come up with newer solutions catering to the changing requirements of such applications (such as low-delay, low power and low complexity encoders). |

- Codec for emerging applications, e.g., VR/AR and IoT

# Research Directions and Recommendations in Future Softwarized Networks

- Strategies for Big Data [365]–[367]
- Scalability, Resilience and QoE Optimization [368-375]
- Network Sharing and Slicing [20], [376–383]
- QoE Business Models [5], [385]
- Network Performance, Evaluation and Benchmarks [386–388]

# Conclusion

- Comprehensive survey of QoE management solutions using SDN and NFV in current and future 5G networks
- Several future directions:
  - QoE-oriented network sharing and slicing
  - QoE business models in softwarized infrastructures
  - intelligent QoE-based big data strategies, scalability, resilience, and optimization in SDN/NFV
  - Network Performance, Evaluation and Benchmarks

# Q&A