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REGULAR PAPER

Wireless multipath video transmission: when IoT video applications meet networking—a survey

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Abstract
Advances in video camera and wireless communication technology have enabled a variety of video applications over the Internet. However, meeting these applications' quality-of-service requirements poses significant challenges to the underlying network and has attracted significant attention from the networking research community. In particular, wireless multipath video transmission has been proposed as a viable alternative to deliver adequate performance to Internet video applications. This survey provides a thorough review of the current state-of-the-art in multipath video transmission focusing on IoT applications. We introduce a taxonomy to classify existing approaches based on their application-specific mechanisms (e.g., video coding techniques) as well as networking-specific techniques. In addition to describing existing approaches in light of the proposed taxonomy, we also discuss directions for future work.

Keywords Wireless video transmission · Internet of things · Wireless multimedia sensor network · Multipath routing · Video coding

1 Introduction

According to a recent report from Cisco [1], 82% of Internet traffic will be video by 2022. This is up from 75% as of 2017 and this trend, which will likely continue, is likely a result of ever-increasing availability of wireless communication infrastructure combined with the proliferation of end-user devices equipped with low-cost, yet relatively powerful video technology, which, in turn, has contributed to the unprecedented growth of a variety of Internet and IoT video applications and services. Such applications include on-demand and live video streaming, monitoring and surveillance, public safety, emergency, and law enforcement, to name a few.

In addition to their high bandwidth demands, video applications also require more stringent quality-of-service guarantees from the network, such as bounded delay and delay jitter to deliver adequate quality-of-experience to users. Meeting such requirements becomes even more challenging in wireless networking environments due their more limited capacity and higher data loss and link failure probability [2]. To mitigate these challenges, approaches based on wireless multipath video transmission have been proposed and have been shown to deliver higher throughput, lower delay, as well as improve network resource utilization through load balancing across multiple paths [3]. However, there is no current one-size-fits-all solution that can cater to the wide variety of video applications. We argue that, as the number and diversity of video applications increase and as wireless networks become more heterogeneous incorporating legacy—as well as new technology (e.g., 5G and beyond, IEEE

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802.11ac, etc.), it is imperative to gain a solid understanding of the interplay between the characteristics and requirements of video applications and the core functions and features of the underlying network to adequately support existing and emerging Internet and IoT video services.

To this end, in this work, we survey the state-of-the-art of wireless multipath video transmission for IoT applications focusing specifically on the interaction between the features and requirements of different IoT video applications and the underlying network. As described in more detail in Sect. 2, existing surveys on wireless multipath video transmission have not explored the relationship between the network and its core functions and the wide range of IoT application scenarios. Generally, they either focus on application or on networking aspects.

The main contributions of our survey can be summarized as follows:

- We identify the main classes of IoT video applications and scenarios, their characteristics, and requirements.
- We propose a taxonomy that maps the design space of wireless multipath video communication by exploring the interplay between IoT application scenarios, their features and requirements, and the core networking functions, i.e., routing and forwarding.
- We use our taxonomy to classify and discuss a broad range of existing wireless multipath video transmission approaches for IoT applications as well as directions for future research.

The rest of this paper is organized as follows: We first review related surveys in Sect. 2 and discuss the main IoT application scenarios in Sect. 3 to contextualizing the contributions of our survey. Then, we propose in Sect. 4 a new component-based taxonomy that allows us to organize the vast literature on the general topic of wireless multipath video transmission focusing on Iot applications. Each component of the proposed taxonomy is then described in detail as follows: Sect. 5 focuses on video services; Sect. 6 on video coding; Sects. 7 and 8 on multipath routing and forwarding, respectively. Finally, Sect. 9 concludes the survey and discusses open research issues.

2 Related surveys

Most surveys on wireless multipath video transmission are dedicated to multipath routing protocols in Wireless Multimedia Sensor Network(WMSN) [4–9]. In [7], several protocols and multipath routing strategies are discussed. It also identifies potential video transmission research directions. The work in [8] analyzes and evaluates the performance of several multipath routing protocols for transmission of image, audio, and video in wireless network. A general classification for the various approaches adopted in multipath routing protocols has been proposed in [9], where different routing metrics are also considered.

Multipath routing protocols for QoS assurance have also been surveyed, including [4, 5]. The work in [4] discusses the issues that should be considered when developing efficient routing protocols to assure applications' QoS. It categorizes QoS routing protocols based on a number of link/path cost metrics for the selection of the next forwarding node or optimal path. It proposes a set of routing metrics to be used jointly to find the cost of a link/path. A comprehensive survey of both best-effort and real-time multipath routing protocols for wireless video transmission is presented in [5]. It introduces a new taxonomy for multipath routing protocols based on methods to improve network capacity and resource utilization.

Given the diversity of multimedia applications, routing protocols for video transmission should account for each application's specific requirements. To our knowledge, there are only a few surveys that take this perspective. A recent survey on wireless multipath routing for video transmission applications was presented in [3]. It considers both application and network aspects and presents a taxonomy from an end-to-end perspective. However, it only considers multipath communication between mobile devices equipped with multiple wireless network interfaces and focuses only on data plane issues, i.e., multipath forwarding mechanisms, leaving out research that focuses on control plane approaches.

Our survey provides a holistic view of wireless multipath video transmission with a focus on IoT applications. It proposes a taxonomy that considers the interplay between core networking functions, notably routing and forwarding, and the wide spectrum of IoT application scenarios and their requirements. Our hope is that our survey and its perspective on the design space of wireless video communication for IoT applications will shed light on open research questions and help guide future work to address them.

3 IoT video application scenarios

There is a wide variety of IoT applications that involve video transmission. In this section, we discuss a number of IoT scenarios and their specific features and requirements regarding video transmission (Fig. 1). Table 1 lists common IoT video applications, their networking requirements, and references to prior work that focus on video transmission in the context of these applications. Note that all references

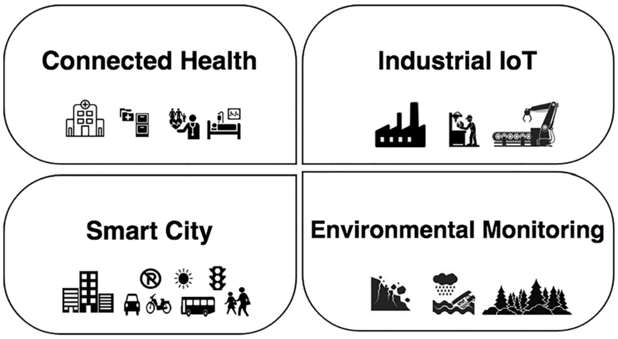


Fig. 1 Examples of IoT video application scenarios

mention reliability as one of the requirements for these applications and several studies consider multipath routing strategies as one of the best ways to achieve reliable video delivery [10–19].

3.1 Connected health

Healthcare systems have been increasingly relying on video for applications such as real-time diagnostics and real-time patient monitoring [20], both in healthcare facilities or at home. Additionally, video from patients can be stored for offline analysis [21].

Telemedicine is another important application that allows patients to be examined remotely by doctors (e.g., specialists) who may not be available where the patient resides. For remote examination, data from other sensor such as body temperature, blood pressure, and breathing activity can also be examined [21]. Telemedicine applications typically require real-time video transmission with low delay and high bandwidth.

To support connected health services, IoT nodes are deployed indoors (e.g., in hospitals, clinics, and patient homes), and, as such, communication may be affected by obstacles, walls, as well as interference from other equipment.

3.2 Industrial IoT

In industrial applications, video can be used in the inspection and control of industrial equipment that requires high accuracy, availability, and reliability to support high-precision manufacturing processes such as those used in semiconductor chips, automobiles, food, or pharmaceutical products [20].

In industrial IoT deployments, cameras are usually installed at different points in industrial plants and may need to operate under challenging conditions. Yet, they may be required to meet stringent quality-of-service requirements such as high bandwidth to deliver high video resolution, high reliability, and low data transmission delay [23].

3.3 Smart city

One of the most common video applications in smart cities is security and surveillance of outdoor or indoor spaces to control access to an area, detect unauthorized visitors, among other purposes [24].

Large urban centers have been adopting camera networks to help manage public transportation, traffic, road conditions, and parking [2]. Video from multiple cameras can be analyzed in real time or offline using computer vision techniques to provide valuable information regarding peak hours, traffic and road conditions/incidents, routes, and more [25].

Note that the network requirements vary with application-specific requirements. For example, traffic management only needs enough reliability to get details to distinguish vehicle contours from the surrounding and track their movement. On the other hand, person tracking applications require high network throughput, because it depends on high-definition video to enable identifying and tracking facial features [24].

Network nodes are usually deployed on poles on the streets [2]. As in all urban environments, wireless communication in smart cities can suffer from large obstacles (such as buildings), noise, and interference. Thus, the systems' performance is also highly dependent on the distribution of the camera nodes, as well as the other aforementioned factors.

Table 1 IoT video applications and their QoS requirements

References	IoT scenarios	Video application	Network requirements mentioned in references
[2, 17, 20–22]	Connected health	Remote patient observation	Security, reliability
		Real-time examination	Throughput, delay, security, reliability
[17, 20, 21, 23]	Industrial IoT	Process control systems	Delay, security, reliability
		Product inspections	Throughput, delay, security, reliability
[6, 17, 22, 24]	Smart city	Person tracking	Throughput, delay, security, reliability
		Vehicle traffic management	Security, reliability
[22, 25]	Environmental monitoring	Forest monitoring	Reliability, energy
		Natural disaster detection	Throughput, delay, reliability, energy

3.4 Environmental monitoring

Environmental monitoring is another important IoT application domain which uses video as well as other types of sensor data to monitor wildlife habitats, forests, and oceans. Such deployments usually target remote, hard to access locations [25] and therefore must be energy-efficient to maximize their operational lifetime independent of human intervention (e.g., battery replacement). In general, multiple cameras are deployed in wide outdoor areas where long-range communication may be needed [22].

In applications for disaster management, like wildfires, floods, or landslides, in addition to reliability and energy efficiency, low latency and high throughput are also required for timely event detection and real-time event tracking [25].

4 Taxonomy

We propose a novel taxonomy that charts the design space of wireless multipath video transmission systems by exploring the interplay between IoT application features and requirements and core networking functions. As such, we examine how aspects specific to IoT video services influence the design of core network protocols as well as how the underlying networking issues play a role in video transmission application design. We then use our taxonomy to classify existing approaches to wireless multipath video transmission for IoT applications.

Examples of application-specific aspects for video transmission include techniques that seek to improve coding efficiency and mechanisms to enhance video compression ratio. Key networking services include efficient routing and forwarding, and reliable encoded/compressed video stream transmission.

To better capture the close interaction between application and networking factors specific to video transmission in IoT scenarios, this survey opted for using unified modeling language (UML [26]) notation to represent its taxonomy. UML was proposed as a way to standardize how software system design and development processes are represented visually. While UML provides a wide range of representations and symbols, for our taxonomy, we use classes and composition and specialization relations. Composition is represented by a filled diamond and a solid line, indicating that one class is composed of others. Specialization is represented by a hollow triangle close to the more generic class in its connection with the more specialized classes.

Our taxonomy was created based on an extensive review of the literature on IoT video transmission, in particular wireless multipath approaches. As will become clear in the remainder of this survey, not every work in the literature tackles all components identified in the taxonomy. Indeed, several proposals focus on a single feature or on a subset thereof. And in fact, one of the important takeaways from our survey and taxonomy is what areas of wireless multipath video transmission targeting IoT applications can benefit from further investigation. Figure 2 illustrates the top layers of our taxonomy showing that existing wireless multipath video transmission proposals typically consist of application and networking components. In turn, the application component may comprise video encoding techniques and other video services, such as real-time or on-demand video streaming. On the other hand, network aspects can be divided into multipath routing and multipath forwarding strategies.

4.1 Application aspects

The main application aspects identified in the multipath video transmission literature focusing on IoT applications were various video coding techniques as well as other video services. Video coding includes video compression as well as error correction techniques. Video services refer to the types of video transmission supported by the application, such as streaming (live or on-demand) as well as different video processing services including computer vision algorithms for target tracking, situation awareness, and multi-camera coordination. As will become clear in this survey, these application features and services can affect both the quality of the video being transmitted as well as how the video flow is transmitted through the network.

4.2 Network aspects

Network aspects underlying multipath video transmission for IoT applications have attracted considerable attention from the research community. Most of the work in the literature focuses on multipath routing—i.e., finding multiple possible routes in the network from source to destination—and forwarding—i.e., once multiple paths are found, how to forward video traffic using these routes.

This survey, like most studies on wireless multipath video transmission, is focused on the requirements of IoT

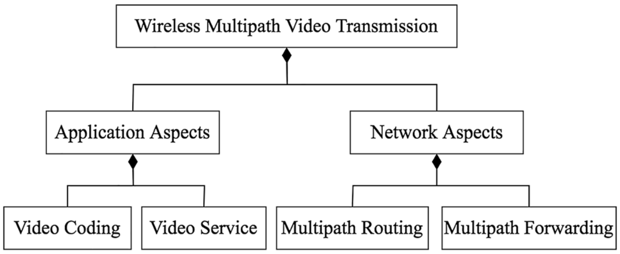


Fig. 2 Wireless multipath video transmission taxonomy for IoT applications

applications that need to transmit multimedia content with a particular level of QoS [8].

Meeting the requirements of IoT applications is challenging due factors such as resource constraints at participating nodes, e.g., limited processing storage, and communication capabilities, as well as battery lifetime.

In video transmission, multipath routing is a fundamental mechanism to determine the network paths that will be used to send video traffic. For example, different routing metrics have been explored with the goal of improving video transmission quality [4]. Moreover, path quality also depends on route discovery and selection mechanisms used by the routing protocol. In this survey, we identify the main building blocks used by existing multipath routing approaches, namely: Route Discovery and Maintenance, Routing Metrics, Multipath Selection, and Multipath Forwarding. We should point out that, in most routing protocols, these components are tightly coupled and their functions may overlap with each other. As discussed in Sects. 7 and 8, conceptually decoupling them facilitates the understanding of the state-of-the-art in wireless multipath routing for video transmission focusing on IoT applications.

Additionally, cross-layer approaches, which allow the exchange of information across multiple protocol layers to improve the performance of multipath video transmission, are also discussed. For instance, video frames can be marked at the application layer according to their importance, allowing the network layer to distinguish them and possibly forwarding them through different paths to improve video delivery quality [27].

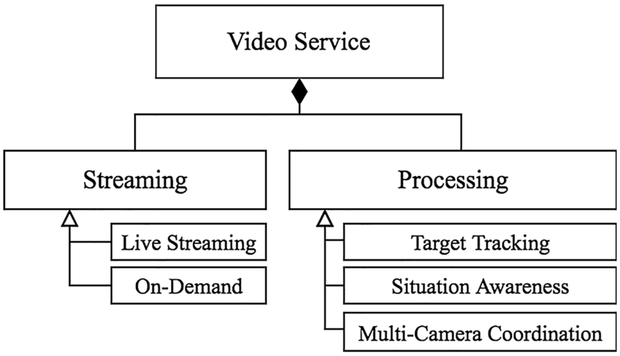


Fig. 3 Video services commonly associated with multipath video transmission

5 Video services

As illustrated in Fig. 3, we consider two different types of video services, namely streaming and processing. Video streaming refers to real-time video transmission where video is transmitted without any processing other than video encoding, while video processing provides additional services to improve performance, increase energy efficiency, or decrease bandwidth requirements.

Table 2 summarizes the main video service components and their definitions as commonly found in the literature.

5.1 Video streaming

Video streaming is commonly used for both live transmission or on-demand services.

5.1.1 Live streaming

In the context of IoT applications, live video is a streaming service in which source cameras capture live videos and stream them to the destination in real time. In live streaming applications, the destination is usually a monitoring center where staff may need to watch videos in real time. Live streaming is particularly challenging due to their stringent delay and throughput requirements as packet retransmission or buffering are typically not an option. Hence, a number of approaches have been proposed to address live streaming's quality-of-service needs, which can be supported by multipath video transmission.

5.1.2 On-demand

On-demand video services allow users to watch a prerecorded video at a desired time. They are widely used

Table 2 Types of video services for wireless multipath video transmission

Video services	Definitions	References
Streaming		
Live	Cameras collect and transmit live video coverage of an event	[12, 14, 15, 18, 19, 27, 27–54]
On-demand	Video is stored so that it can be latter requested by users	[10, 55–60]
Processing		
Target tracking	Recognition and tracking of people or objects	[16, 17, 25, 61, 62]
Situation awareness	Aggregation of perception information to reduce data transmission	[8, 25, 61, 63, 64]
Multi-camera coordination	Coordination between neighboring cameras to share or fuse their videos	[65–67]

in a variety of domains such as video-analytics applications for public safety and traffic planning in smart cities. In these applications, videos are captured and stored for future on-demand viewing. The server where the video is stored may also perform some processing to filter and extract information about the scenes—for example, activity analysis. This processing, however, does not have the same real-time constraints as those of live streaming, such as a maximum end-to-end delay. In contrast to live streaming, users can fast-forward, rewind, and playback the video as many times as necessary. Therefore, buffering can be used more aggressively. Some notable efforts that consider exclusively on-demand video transmission include [10, 55–60].

5.2 Video processing

Video processing services are typically used by video applications to reduce transmission of redundant information, perform preliminary video processing such as combining data originated from multiple views, on different media, or with different resolutions, as well as filtering and extracting semantically relevant information from the environment. Additionally, video processing algorithms can be performed by network nodes along the transmission paths. Figure 4 illustrates the main video processing services identified in the literature.

5.2.1 Target tracking

Target tracking, which is the main focus of the work reported in studies [16, 17, 25, 61, 62], aims to identify a person or object in motion, enabling cameras to follow the target. Access control and surveillance applications as well as habitat monitoring is some of the applications that employ target tracking.

Target tracking usually consists of three phases: target detection, recognition, and tracking. Detection refers to identifying the presence of a new target whenever it enters the monitored environment. Recognition is used to determine if the object is of interest and whether further processing is warranted. Finally, tracking consists of enabling cameras to follow the target as it moves through the environment.

5.2.2 Situation awareness

Many applications do not need raw video to be transmitted all the time [63]. For example, in surveillance or event tracking applications, as long as there are events detected, video can be compressed to a simple scalar value or not be transmitted altogether. In environmental monitoring applications, weather data can be used to enable video cameras, as well as distributed filtering techniques can be applied to create time-lapse images to produce some forecast patterns that can anticipate future disasters [20].

These types of video processing rely on the perception of certain elements in the environment to decide whether or not to transmit raw video, snippets of the video, or simply a scalar value. As such, they can dramatically reduce the amount of data transmitted over the network, therefore optimizing network resource utilization and energy efficiency.

SensEye [25] is a notable example of an approach that uses a hierarchical architecture for energy-efficient event tracking. They propose a two-tier camera deployment where the bottom tier consists of low-power cameras which trigger higher resolution cameras at the top tier in an on-demand fashion. Another hierarchical deployment-based approach for critical-event surveillance was proposed in [64] which uses densely deployed low-cost audio sensor nodes as the bottom tier, while the second tier is equipped with high-cost sparsely deployed rotational video nodes. The first tier performs the preliminary audio event detection task that sends an alarm message to activate the rotational video nodes to cover the event. Another example of a system that uses video processing was proposed in [61] where a processing proxy server analyzes all video flows and only alerts the monitoring center if relevant events are detected.

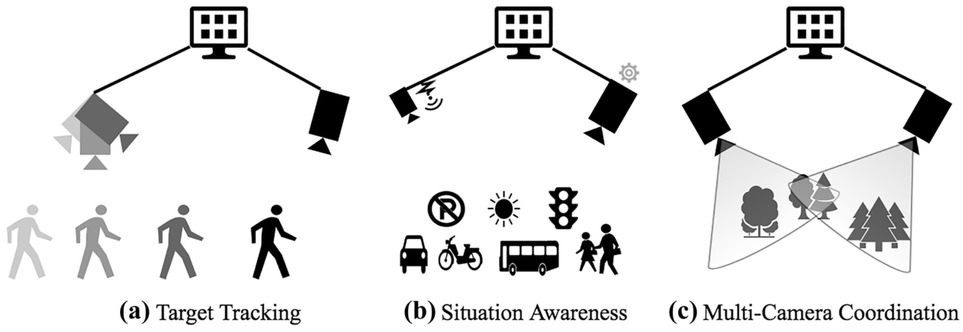


Fig. 4 Different types of video processing services

5.2.3 Multi-camera coordination

This is a service typically used by applications such as surveillance, target tracking, and control of automated systems where multiple cameras fuse their videos. Natarajan et al. [65] present a survey of various techniques for multi-camera coordination and control that have been adopted in surveillance systems.

Multi-camera coordination can also provide support to free-viewpoint applications. Free-viewpoint video is a technology that enables 3D visualization of a scene by freely changing the viewpoints. Liu et al. [66] proposed a system for multipath transmission of free-viewpoint video with joint recovery capability for both inter-view (left and right views) and temporal description. The proposed approach correlates viewpoint similarities from two nearby cameras. This technology enables motion parallax—a viewer's head movement triggers a corresponding shift in the viewing perspective of the observed scene. Depending on the intermediate virtual view currently requested by the client, texture and depth maps from the two nearest camera viewpoints are encoded for transmission.

A framework for transmitting real-time surveillance video with a wide-viewing-angle and high resolution using multi-cameras was proposed in [67]. They consider a video-surveillance scenario in which the signals from two rotatable monitoring cameras can be combined to obtain a wider viewing angle. A video mosaicing method is adopted to merge the videos generated by the two cameras into one seamless video, which is transferred to the destination in real time.

5.3 Summary

Video processing services usually complement video streaming services. In this section, we intended to identify the video streaming and additional processing services indicated for the proposed multipath video transmission found in the literature. Table 3 summarizes the different video streaming and video processing services found in the literature. We observe that while most studies focus mainly on video streaming services, in particular live streaming, video processing is also tackled by a significant number of references. This observation indicates that one needs to consider the type of video service used by IoT applications when designing multipath video transmission because of their different quality-of-service requirements.

6 Video coding

As illustrated in Fig. 5, the main video coding techniques explored in the literature are compression and error correction. Video coding technologies have been extensively used as a way to increase video compression ratio as well as improve the efficiency and visual video quality. Many

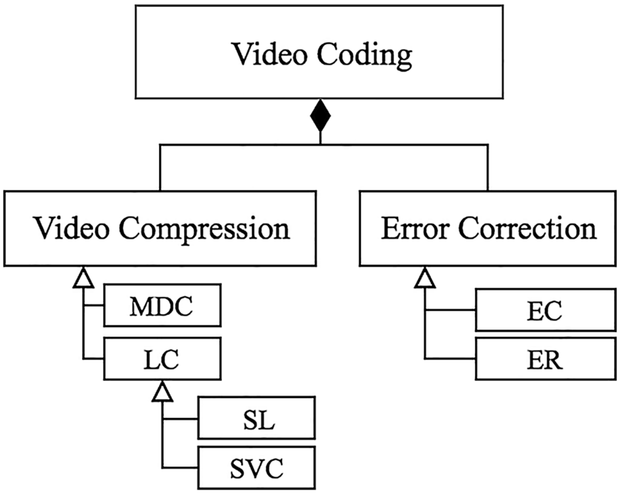


Fig. 5 Classification of video coding techniques for multipath video transmission

Table 3 State-of-the-art in video streaming and video processing

References	Video streaming		Processing		
	Live	On-demand	Target tracking	Situation awareness	Multi-camera coordination
[12, 14, 15, 18, 19, 27, 27–54]	✓				
[10, 37, 55–60, 68]		✓			
[61]	✓		✓		
[25]		✓	✓		
[64]	✓		✓		✓
[17]	✓	✓		✓	
[16, 62]	✓			✓	
[63]	✓	✓		✓	
[66, 67]	✓				✓

studies explore video compression techniques that split the video stream into sub-streams to transmit over different paths. Some of them adopt error correction techniques to provide greater reliability.

Video compression techniques fall into two basic types, namely layered coding (LC) and multiple description coding (MDC). Both generate multiple sub-streams that can be transmitted over multiple paths. In LC, the sub-streams are mapped into layers where the base layer stream is the most important and provides a basic quality level that can be improved with additional enhancement layers. LC techniques can be classified as single layer (SL) and scalable video coding (SVC), where SL generates a single video stream for transmission, while SVC encodes the video as a set of hierarchically layered sub-streams. In MDC, all sub-streams have equal importance, as different quality levels can be obtained with different combinations of sub-streams.

Error correction techniques can be categorized according to the roles performed by the encoder and decoder. In error resilience (ER), the encoder adds redundancy to the video streams, allowing certain levels of errors to be recovered at the decoder. Error concealment (EC), on the other hand, adds post-processing methods to the decoding process to improve the perceived quality of the reproduced stream in face of errors.

6.1 Video compression

Video compression techniques segment each frame into processing units called macroblocks which are then compressed to reduce the required bandwidth to transmit the video while maintaining acceptable visual quality. Compression exploits macroblocks' spatial and temporal correlations as specified by video coding standards.

For example, MPEG video compression [69] segments the video sequence into groups of pictures (GOPs) that determine the organization of frames. Each group includes three types of frames: intra (I-frame), predictive (P-frame), and bidirectional (B-frame). I-frames are compressed independently and do not require additional information to be reconstructed. They are used as references for forward and/or backward prediction to decompress the P- and B-frames.

MPEG video compression standardizes decoder structures and bitrates to enable development of efficient encoding algorithms. It supports a wide range of application-specific parameters and provides a framework for extending layered coding and multiple description coding as a way to support emerging video applications.

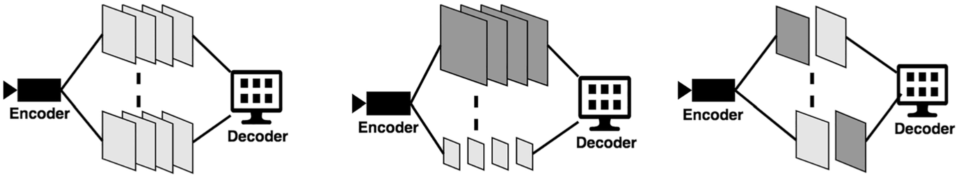
The H.264/AVC advanced video coding standard has been widely used by high-definition (HD) video applications [18]. More recently, the H.265/HEVC high-efficiency video coding standard has emerged to support ultra-high-definition (UHD) video transmissions and provide less bitrate. While more complex, H.265 results in almost 50% bandwidth requirement reduction compared to H.264/AVC at the same reproduction quality [68]. The main advantage of H.265/HEVC is the use of more flexible macroblocks—fundamental unit of the video coding process, allowing encoding predictive macroblocks of different sizes.

Some early multipath video transmission approaches have adopted the H.264/AVC and H.265/HEVC video coding standards with SL techniques. However, more recent studies have proposed scalable extensions using SVC and MDC techniques. These different approaches are discussed in more detail below and are illustrated in Fig. 6.

6.1.1 Layered coding

LC has become part of the of established video compression standards [55, 70]. It provides layered embedded bitstreams that are generated at different bitrates, encoding a video sequence into multiple layers without compromising video quality. Layered representations provide a convenient way to perform rate control to mitigate network congestion and can use single or scalable layers.

Single layer SL techniques perform video compression using only one layer. Approaches to multipath video transmission with SL have adopted the H.264/AVC and H.265/HEVC standards [10, 12, 15, 17, 18, 27, 28, 34–36, 61, 62, 71]. In general, the video is segmented into GOPs which are encoded and transmitted on different paths. The better paths—selected based on routing metric—are dedicated to I-frames, since video decoding relies heavily on I-frames and I-frames which require higher bandwidth than P- and B-frames. P- and B-frames can be transmitted using alternate, lower bandwidth paths. B-frames typically have the lowest bandwidth requirement and B-frame encoding requires the acquisition of the corresponding I-frame or P-frame, which introduces delay. For this reason, some



(a) Single Layer **(b)** Scalable Video Coding **(c)** Multiple Description Coding

Fig. 6 Video compression techniques

proposals only use I-frame and P-frame encoding modes [12, 61].

Scalable video coding In SVC, the video streams are divided into a base layer and one or more enhancement layers. SVC layers are hierarchical: a given layer cannot be decoded unless all of its lower layers have been received correctly. Enhancement layers complement the base layer to improve visual quality in terms of temporal, spatial, and SNR (signal-to-noise ratio) scalable modalities. The MPEG standards include extension tools to support these SVC modes. The scalable extensions for the H.264/AVC and H.265/HEVC standards are called H.264/SVC (Scalable Video Coding) and H.265/SHVC (Scalable High-definition Video Coding), respectively.

Generally, multipath proposals based on H.264/SVC transmit the base layer over the better paths and the enhancement layers over the marginal paths [33, 37–39, 56, 59]. Furthermore, the H.265/SHVC encoding was adopted in [30, 31, 68] due to the better compression, reducing latency and bitrate. With H.265/SHVC, the control of the bitrate of each layer can be handled according to the the bandwidth available for each path.

SVC can be extended to address application-specific requirements. As an example, a reference-frame-cache-based surveillance video transmission system (RSVTS) was proposed in [67]. It is an H.264/SVC extension which implements a method for merging multiple rotatable cameras to deliver wide-viewing-angle and high-definition video. In addition, it implements a reference frame cache on both the sender and receiver sides to improve video quality by increasing the probability to achieve adequate decoded video quality. The scalable High-efficiency Inter-layer Prediction-based Video coding (SHIPVC) was proposed in [45]. It extends H.265/SHVC to implement two-layer predictions such as texture color and motion with different quantization parameters.

6.1.2 Multiple description coding

MDC has been proposed as an alternative to layered coding for video streaming [55]. Each description alone can guarantee a basic level of reconstruction quality at the decoder, while additional descriptions further improve quality.

The key idea of MDC is to partition the video stream into two or more independently decodable and mutually refinable descriptions. Several techniques to generate video descriptions using MDC are discussed in [72]. The number of descriptions can be defined according to application requirements, and the partitioning may be in the spatial or temporal domains. In the spatial domain, the descriptions are generated by a process performed at the pixel level. In temporal domain MDC, the descriptions are generated by a process performed at the frame level. Each description's individual packets can be transmitted separately through different paths. If packets are lost, the video may still be successfully decoded using packets carrying the other descriptions, albeit with lower fidelity. As such, MDC provides a solution to mitigate video quality degradation in the presence of packet losses, bit errors, and burst errors during transmission [40].

The combination of MDC with multipath routing has been proposed to reduce network congestion by exploring path diversity to balance traffic load [29, 40–43, 60, 63, 73]. Some studies propose to classify descriptions to define packet priorities and thus improve MDC video streaming robustness [32, 42].

A texture-plus-depth format of free-viewpoint video was proposed in [66]. It employs MDC with H.264/AVC for a multi-view representation where multiple texture maps from closely spaced capturing cameras are encoded into one bit-stream.

One way to generate MDC is to explore the GOP or macroblock structure of MPEG video coding standards. In this context, studies suggest the flexible macroblock ordering (FMO) of the H.264/AVC standard as more appropriate [41, 44, 66]. FMO refers to rearranging macroblocks in groups where each group is a description of the video according to specific standards.

Hybrid approaches combining the advantages of both SVC and MDC techniques have also been proposed [14, 44, 46]. In these approaches, the descriptions of each layer are generated in the FMO format. Then, macroblocks of each layer are sent over disjoint paths.

Video coding can also also generate variable bitrate during packet forwarding to maintain the quality of video transmission when facing limited available bandwidth. In this way, some studies have proposed adaptive video coding to reduce the number of video frames or number of enhancement layers to reduce the required bitrate. Cross-layered designs have been proposed to control the bitrate [35–37, 68]. In these designs, each layer of an encoded video stream is handled according to the status of the available bandwidth. In [59], the available bandwidth of the different paths is estimated to determine the number of enhancement layers and select optimal paths to transmit each layer.

In adaptive video coding forwarding, video packets are encoded at the source node, but intermediate nodes can re-encode them before forwarding. This type of coding presented in [33] is called intra-session network coding or transcoding and can adapt to the available network bandwidth and improve video streaming quality.

6.2 Error correction techniques

Error correction techniques have been proposed for multipath video transmission to mitigate the effect of packet losses due to network congestion and transmission errors and thus limit their impact of video distortion and video quality deterioration. Typically, error correction techniques are integrated into video compression to improve the reliability and robustness of video decoding. In the specific case of multipath video transmission, the main techniques adopted in prior work are error resilience (ER) and error concealment (EC).

6.2.1 Error resilience

Error resilience techniques aim to minimize the transmission errors' impact upon video decoding. ER can be combined with layered coding techniques. For example, it can set optimal video compression parameters in SL to generate packet flows that respect the capacities of the network. Recommendations for setting the coding parameters can be provided by the physical layer and sent from destination to source. This way, each source node can adopt different parameter settings according to the channel state, such as link reliability and stability. Thus, some studies have proposed that the destination periodically sends the recommended video compression parameters after analyzing the video received during the previous period in different states of the wireless channel [35, 36].

In ER, the encoder also adds redundant packets at the transmission source to enable error detection and correction. This well-known technique is also known as forward error correction (FEC).

An overview of ER techniques for scalable video coding (SVC) referred to as inter-layer FEC is presented in [70]. Most approaches combine ER with video compression to protect the base layer using the enhancement layers [33, 44]. In [44], the base layer is duplicated and transmitted as redundant packets over different paths. In [33], packets with the highest priority (e.g., I-frames) are re-encoded with redundant data during generation.

ER can also be combined with multiple description coding (MDC) [48, 60, 66]. In [66], redundant packets are generated for all MDC descriptions. The work reported in [48] proposes adaptive ER algorithms that dynamically generate redundant packets based on current network conditions.

6.2.2 Error concealment

In error concealment techniques, the decoder tries to compensate for missing information, so that the visual quality of the reproduced video is not severely compromised. EC can exploit spatial and temporal redundancy in video compression to recover from network losses.

A survey of EC techniques applied to layered coding (LC) [74] grouped existing approaches into intra-layer EC and inter-layer EC. Intra-layer EC explores the spatial domain based on pixel, using either texture features or edge/object-shape information to conceal lost frames. Inter-layer EC uses temporal information to estimate the lost motion vectors, which are used to recover damaged macroblocks by considering a reference frame. Usually, only one of those methods is suitable for whole-frame, although it is possible to use both or different method for each macroblock.

When SVC is used for coding, it can improve the EC by exploiting the similarity among the layers. In this approach when a macroblock, slice, or a frame of the enhancement layer is lost, the corresponding part of the frame in the base layer can be used to conceal the lost data [44].

In [68], a cross-layer framework for video streaming with inter-layer EC was proposed. It applies EC based on feedback messages aiming to improve the end-to-end QoS and to provide smooth video streaming. If some video frames are missing, then an SVC with EC scheme is used to estimate and recover the missing video frames. This scheme is executed on the base layer to maintain a minimum level of QoE.

Another inter-layer EC method is proposed in [45]. Missing video frames are identified based on the sequence number in the packet header information. The missing frames are concealed by computing a motion vector extrapolation based on two consecutively received frames.

6.3 Summary

Table 4 summarizes the different video coding techniques discussed in this section. There are basically two types of video compression techniques—multiple description and layered video coding; both of them encode a video sequence in a way that multiple levels of quality can be obtained depending on the parts that are received. In LC, although many studies adopt only a single layer, SVC has been widely used offering special protection for the base layer. MDC has been explored considering the diversity of systems where each description has an equal probability of decoding. In addition, some studies have proposed a combination of MDC and SVC.

While EC techniques can improve video coding robustness, they can also increase video compression complexity, generate additional data (increasing bandwidth requirements for video transmission), worsen network congestion, and increase processing delays [68]. Thus, while the literature has contemplated different combinations of compression and error correction techniques, there are still many challenges to be addressed in the context of multipath video transmission.

Table 4 Summary of prior work using video coding techniques classified as video compression and error correction

References	Video compression				Error correction	
	SL	SVC	MDC	Standard	ER	EC
[10, 12, 15, 17, 18, 27, 28, 34, 61, 62]	✓			H.264/AVC		
[35, 36]	✓			H.264/AVC	✓	
[37–39, 56, 57, 59]		✓		H.264/SVC		
[33]		✓		H.264/SVC	✓	
[30, 31, 68]		✓		H.265/SHVC		✓
[29, 41, 43, 71]			✓	H.263-		
[40, 42, 47, 63, 66]			✓	H.264/AVC		
[48, 60]			✓	H.264/AVC	✓	
[32]			✓	H.264/SVC		
[14]		✓	✓	H.264/SVC		
[44, 46]		✓	✓	H.264/SVC	✓	✓
[67]		✓		H.264/RSVTS		
[45]		✓		H.265/SHIPVC		✓

7 Multipath routing

Multipath routing protocols for wireless video transmission are surveyed in [5, 6, 8, 9]. They are classified based on the reliability requirement and QoS constraints of multimedia applications. Reliability has emerged as an important aspect of multipath routing protocols motivated by various multimedia applications, notably services that require reliable monitoring. Existing multipath routing protocols that seek to satisfy reliability requirements include multipath multi-SPEED (MMSPEED) [11], reliable information forwarding multiple paths (ReInForM) [13], and network coding-reliable multipath routing (NC-RMR) [75], while the main protocols that satisfy multipath QoS constraints are sequential assignment routing (SAR) [76] and stateless protocol for real-time communications in sensor networks, called SPEED [77].

More recent studies propose extensions to traditional wireless ad hoc routing approaches that incorporate multipath mechanisms for video transmission [14, 18, 39, 47, 63].

Considering the state-of-the-art in multipath routing for wireless video transmission, we classify multipath routing protocols based on their fundamental building blocks, which include their route discovery mechanism, routing metric(s), and path selection strategy. It is worth noting that, in most existing routing protocols, these basic functions are usually intertwined and not easily decoupled. One of the goals of our classification is to disentangle them to better understand the fundamental differences between proposed existing routing approaches and how they can be improved. Figure 7 illustrates the proposed classification of multipath routing building blocks for wireless video transmission aiming at IoT applications.

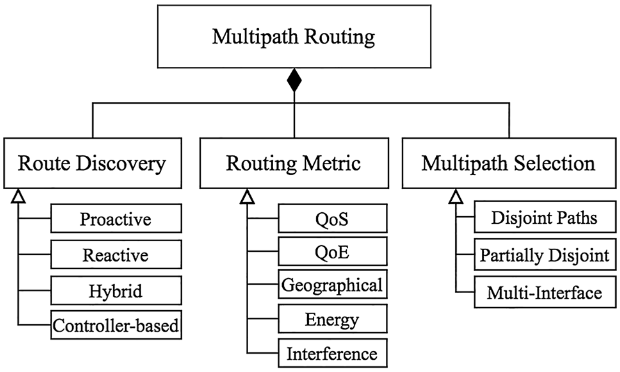


Fig. 7 Multipath routing classification for wireless video transmission in IoT scenarios

7.1 Route discovery

Route discovery is the first phase of the routing protocol in which a source node tries to find the available paths to a specific destination. In this procedure, each node performs neighbor discovery by exchanging control messages between them. In the same way, nodes also perform the route maintenance by identifying broken paths that have been found. Our literature survey indicates that existing multipath routing approaches have not proposed novel route discovery and maintenance mechanisms, in particular techniques that consider application-specific requirements for multipath video transmission. In general, variants of traditional routing protocols have been adapted to provide routing over multiple paths.

Route discovery mechanisms are traditionally classified as reactive, proactive, or hybrid. In this survey, we also consider controller-based approaches in which a controller provides core networking functions, including route discovery. These approaches were inspired and motivated by the software-defined networking (SDN) paradigm [28, 30, 31, 49].

7.1.1 Proactive

In proactive routing approaches, routes for every destination are proactively discovered based on table driven, so that, when a source has data to send to a destination, a route has already been discovered. As such, routes are periodically updated, e.g., by periodically updating routing tables in each node. Topology updates are usually gathered by means of control messages exchanged periodically between nodes. The bandwidth overhead generated by topology updates can be reduced in application scenarios that consider fixed monitoring cameras, because topology changes are less frequently. For example, in video-surveillance applications, nodes are typically stationary and powered by continuous power sources. Therefore, video-surveillance applications have used proactive routing approaches, since they yield reduced packet delays [61].

Some studies proposed proactive multipath routing to improve QoS for video applications [14, 18, 29, 41]. A multipath extension to traditional destination sequenced distance vector (DSDV) is evaluated in [14]. In DSDV, each node maintains a routing table listing all the other nodes they have known either directly or through some neighbors. The proposal extends DSDV by adding new routing table fields to store information about multiple disjoint paths. This mechanism demonstrated good performance for video transmission in terms of loss rate and network load for large networks.

Based on the original optimized link state routing (OLSR) protocol, a QoS multipath routing approach for wireless video transmission was proposed in [18]. OLSR constitutes a more organized and efficient way to manage routes between nodes, and it performs a shortest path algorithm (e.g., Dijkstra) in its complete view of the topology. This extension modifies OLSR's route discovery to estimate link delay between nodes and then performs a multipath Dijkstra algorithm using delay—instead of hop count—to calculate multiple shortest paths.

7.1.2 Reactive

In reactive routing approaches, route discovery is triggered on-demand when a source has data to send, in this case, when the source wants to start video transmission. Typically, if the source does not have route information for the intended destination in its local routing table, it initiates the route discovery mechanism by sending out special messages, usually referred to as "route requests". Existing multipath video transmission approaches that use reactive routing have adopted extensions to traditional single path using source routing algorithms or routing tables, such as dynamic source routing (DSR) [78] and ad hoc on-demand distance vector (AODV) [79], seeking to improve video transmission QoS.

In source routing, the entire path from source to destination is maintained at the source node, who includes path information in the data packet headers. Despite higher header overhead, this mechanism allows each source node to select and control the routes used in forwarding its packets. An evaluation of a QoS-aware multipath extension to the DSR protocol, presented in [63], shows good throughput performance for high data rate video traffic. Also, based on DSR, an adaptive-multipath protocol is proposed in [71]. It aims to improve end-to-end performance of video services providing dynamic self-configuration depending on the state of the network, which is used by the source nodes to make proper multipath selection. In the same way, [12] proposes a path selection mechanism for the split multipath routing (SMR) source routing protocol, reducing the frequency of route discovery processes and control message overhead.

In routing table-based approaches, nodes maintain a routing table with the next hop to the destination. Most studies focusing on multipath video transmission adopt the ad hoc on-demand multiple path distance vector (AOMDV) routing algorithm [15, 35, 36, 39, 42, 47]. It is an extension of the traditional AOMDV [80] protocol for finding multiple, loop-free and link-disjoint paths.

There are other AOMDV extensions proposed for video transmission. One of these extensions is evaluated in [63] and incorporates a multi-criteria decision approach which is shown to outperform video transmission using the original AOMDV in terms of throughput, delay, and reliable delivery.

Another multipath variant of AODV that aims at improving video transmission QoS is evaluated in [14]. It demonstrates the advantages of reactive routing for video transmission in terms of throughput and network load in scenarios subject to high mobility.

7.1.3 Hybrid

Hybrid route discovery tries to combine the advantages of both proactive and reactive routing. A hybrid real-time video stream routing protocol is proposed in [17]. It divides the complete network into corona with the data sink in the center. Proactive route discovery maintains a corona identification for each candidate node based on its distance to the sink, and then, a reactive mechanism computes hop-by-hop the optimal forwarding choice from a source that has high corona identification to zero corona that is the sink node.

Motivated by achieving adequate balance between scalability and efficiency, in [16, 51, 53, 54], a proactive mechanism periodically assigns the node geographic location to its directly connected neighbors, and then, each node decides on-demand which paths should be considered when forwarding packets.

7.1.4 Controller-based

Software defined networking (SDN) [81] has been proposed with the goal to decouple the network control plane from the data plane. According to the SDN paradigm, a controller centralizes routing decisions, while network nodes perform only forwarding. Several studies for multipath video transmission follow this paradigm, centralizing route information at the controller which then computes routes and adds corresponding routing information to routing tables at the forwarding network elements. As the controller has a global view of the network topology and conditions, routing decisions can be simplified. In the context of multipath video transmission, there are proposals where links that do not have enough bandwidth for real-time video streams are not considered when computing routes [28], as well as efforts that periodically monitor the quality of links for video streaming [49].

In [30, 31], an approach that combines controller assistance and source routing is used for multipath video transmission in SDN-based networks. This approach implements a source routing using segment routing paradigm which the source chooses a path and encodes it in the packet header as an ordered list of segments. It increases routing efficiency by improving the capability of selecting paths and thus speeds up video transmission.

While video transmission approaches that leverage controller assistance in SDN-based networks can benefit from SDN's network control flexibility and efficiency, there are still open issues on how route discovery should be designed to consider the interplay with video applications.

7.2 Routing metric

Routing metrics adopted for multipath selection are essential to improve video transmission. Our taxonomy considers the most commonly found metrics for multipath video transmission. However, these classes are not mutually exclusive, since several studies integrate multiple metrics into a single solution. These metrics are described as follows.

7.2.1 Quality-of-service

This is the main routing metric adopted in almost all multipath video transmission proposals due to the video streaming constraints. There are different QoS measures concerning aspects of delay, throughput, and packet loss associated with application requirements. As such, some studies [19, 27] have presented metrics that try to balance several QoS parameters seeking high throughput, low delay, and proper packet delivery. On the other hand, some studies have considered the hop count and geographic distance as factors strongly correlated to QoS [45, 50, 51].

End-to-end delay is also usually adopted, because the delay constraint is precisely necessary for critical IoT video applications, as is the case of health and surveillance systems. In [12, 18, 43], end-to-end delay paths are simply measured by the sum of hop delays, without considering other factors such as link congestion that comes from multiple video sources.

Although QoS is the main metric used in studies for multipath video transmission, care has to be taken as optimizing one QoS metric can compromise performance in other aspects. For instance, minimizing end-to-end delay may require consuming more energy due to the increase of transmitted power.

7.2.2 Quality of experience

This is a metric adopted to evaluate and present subjective study results. However, some studies have also used QoE estimates based on QoS parameters as routing metrics [30, 31, 37, 38, 40, 68]. Hence, these studies present a QoE model to estimate the mean opinion score (MOS) considering the bitrate of the transmitted video and other QoS parameters. MOS is an indicator of QoE that can be used to assess video quality, which is divided into five levels corresponding to the users' perception. In this case, QoE-based protocols seek to maximize the MOS. It is a great routing metric for multipath video transmission, but it requires a lot of resources and cannot be obtained automatically [38].

To achieve perceptual quality evaluation in real time, some studies have adopted the pseudo-subjective quality assessment (PSQA), which is a tool based on statistical learning using random neural network (RNN) [40]. The idea is to train the RNN to learn the mapping between QoE scores and QoS parameters. In this case, the route discovery and the multipath selection mechanisms can be aware of any episodes of QoE degradation.

7.2.3 Geographical

In these approaches, the video source maintains geographical information about its neighbors and the destination to select the best relays. Based on the geographical distances between each possible next-hop and the destination node, they perform an efficient route selection [51–54, 62, 68]. Implicitly, they assume that the Euclidian distance between nodes is a good indicator of energy-efficient paths with good QoS. However, we cannot assume this for IoT application scenarios, especially the smart cities scenario where there are large communication blocking obstacles such as walls or buildings.

To optimize QoS with the minimum geographic distance transmission over the network, a multipath genetic algorithm is proposed in [45]. It seeks to maximize fault tolerance with minimum communication delay during video transmission. The fault tolerance of the path is estimated by the links' quality estimation and neighbor distance. The geographical metric associated with fault tolerance showed improvement with different strategies of video coding and multipath routing. Although the authors affirm that it can be adjusted for a variety of related applications, they also do not consider obstacles in these application scenarios.

To provide delay and energy balance in video transmission, Hossain et al. [50] propose a multipath routing generation algorithm based on geographical information. It defines a model on the basis of traditional spline path generation planning to generate a set of paths uniformly distributed in multiple spaces between source and destination nodes. In fact, the algorithm generates paths with lower interference which is uniformly distributed. However, it depends on a highly dense network in addition to not being designed for multiple video sources.

7.2.4 Energy efficient

This routing metric is essential in IoT application scenarios where nodes are battery-powered. In this context, some studies have proposed this routing metric which aims to minimize the energy consumption of each node [15, 17, 35, 36]. They have recommended that a cost function considers the remaining energy to dynamically choose the video transmission power—and consequently, the communication range—of each node to maximize the network lifetime. Besides these, some studies have proposed a model to estimate the energy consumption on the basis of geographical distance [27, 45, 52–54, 64]. In [64], this is combined with an event detection approach where a minimum number of nodes remain awaken for transmission according to the event, while others get to sleep to maximize energy efficiency. These models aim to minimize energy without considering video application requirements, such as end-to-end delay. The balance between energy and delay, for example, is fundamental for multipath video transmission [50].

Other studies attempt to balance energy usage of all nodes [16, 50]. They use the end-to-end delay required by video applications in their models. As these energy consumption models are based on simple geographical distance, they are also not indicated for IoT application scenarios, as mentioned before.

7.2.5 Interference

Video transmission may be degraded by the interference caused by network flows that share the same nodes or links. Node-disjoint multipath selection mechanisms are used as a simple solution in [17, 27], but they have topological constraints that may not be met in all IoT application scenarios. As an alternative, some proposals relax those constraints by allowing partially disjoint paths with low levels of interference [41, 51, 53, 54, 62]. To this end, they estimate interference levels based on the link quality indicator (LQI), signal-to-noise ratio (SNR), or simply the distance between nodes.

A multicommodity network flows model which considers inter-flow interference is adopted in [37, 38, 82]. Based on this model, the optimization problem to maximize the quality of paths is formulated as a mixed-integer linear problem under link capacity constraint. The link capacity constraint is defined to optimize the amount of video flows over links; however, it assumes flows with the same destination as only one commodity, regardless of their sources.

Another interference metric that aims to maximize the aggregated network throughput considering inter-flow interference is proposed in [73]. It is implemented using the algorithmic framework for throughput estimator (AFTER) [83], an on-the-fly algorithm for real-time throughput estimate that considers a global view of the network. In this case, it proposes a multipath selection mechanism for wireless video-surveillance systems assuming flows between multiple sources and a destination.

7.3 Multipath selection

A multipath selection mechanism is used for choosing the best paths among the discovered routes. While the route discovery process finds possibly all available paths between source and destination, route selection chooses a subset of those to construct a multipath route.

In proactive route discovery, just one additional multipath selection mechanism must be added to the processing of routing update messages to obtain other possible paths at each node. In reactive route discovery, a multipath selection mechanism must be added to collect and store more than one path between the source and the destination. For this, it usually does not discard the duplicate of received route messages at a node to find additional paths.

In general, approaches found in the literature have considered the disjoint and partially disjoint paths techniques for multipath selection. Furthermore, other proposals assume that each node possesses multiple radio interfaces—often of different technologies—each of which provides a feasible path to the destination.

7.3.1 Disjoint paths

This technique is prevalent in the literature, because of the independence and resilience of the paths it discovers. Two paths are said to be disjoint if they have no nodes or links in common. Several studies assume that there are multiple node-disjoint paths available between each pair of nodes [12, 16, 19, 37, 41, 44, 50–54, 62, 68]. The existence of node-disjoint paths, however, is topology-dependent and, thus, such paths may not exist in all cases. Because of that, some studies have considered link-disjoint paths [12, 18], which are more likely to occur. Disjoint paths may be less affected by interference, but that does not necessarily guarantee optimality of the path selection in terms of other performance criteria.

7.3.2 Partially disjoint paths

Path diversity can be explored if the concept of disjointness is made flexible by considering partially disjoint paths. Therefore, this technique is proposed in several studies [17, 38, 43, 45, 64] motivated by the fact that even link-disjoint paths may be unavailable when nodes are deployed randomly. Furthermore, it can optimize multipath selection evaluating all available paths according to routing metrics, without the strict disjointedness constraint. [27, 29, 49]. Another approach of partially disjoint paths is the idea of braided paths, where intermediate nodes process the traffic to select the next nodes that create better multipath [75]. It uses the disjoint paths technique to build actual paths, which are called main paths. Some braided paths on each main path are built according to a braided multipath algorithm.

7.3.3 Multi-interface

Another approach to multipath transmission is to use multiple radio interfaces such as cellular and Wi-Fi networks. It can simplify the multipath selection mechanism by requiring just evaluating the interfaces that meet the routing metrics to select the better paths. For this, the studies [10, 30, 31, 34, 48, 56, 57] have proposed the use of the multipath TCP (MPTCP [84]) transport protocol. MPTCP provides support for simultaneous multipath transmission, multiplexing the data transmitted by each one. Thus, a multipath selection mechanism can be implemented to evaluate the paths of each radio interface and then perform multipath allocations to the video sub-streams. However, it only seems suitable for scenarios with client–server communication in fixed topologies. In addition, for live streaming services, it is necessary to evaluate the path asymmetry in different access networks and the disadvantages of the data retransmission mechanism in MPTCP.

7.4 Summary

The literature has contemplated several multipath routing mechanisms, spanning different aspects of routing. However, no consensus solution has emerged thus far, as multiple issues remain open. Table 5 summarizes the different multipath routing proposals found on the literature according to the three components discussed in this section: route discovery mechanism, routing metric, and multipath selection.

8 Multipath forwarding

A multipath forwarding mechanism determines the packet forwarding strategy of the video streams over the multiple paths selected by routing. At the most basic level, strategies can be divided into concurrent and alternative multipath forwarding, as illustrated in Fig. 8. Within those categories, however, proposals found in the literature can differ quite a bit, originating several specializations.

8.1 Concurrent multipath forwarding

Concurrent forwarding is the main strategy used to improve reliability. It implements video transmission using multiple paths simultaneously. In general, concurrent forwarding approaches propose cross-layer designs to integrate video coding at the application layer with packet transmissions between the network and physical layers. The video coding is responsible to perform packet segmentation or generates duplicated packets according to concurrent forwarding approaches. As illustrated in the taxonomy presented in Fig. 8, in this work, we classify the approaches for concurrent forwarding into Path Scheduling and Duplicate Packet.

8.1.1 Path scheduling

In this concurrent forwarding approach, the packets can be scheduled for forwarding according to their priority, path capacity, or schedule policies.

In packet priority, packets are identified at the application layer that communicates with the network layer to define the forwarding according to their priority. Proposals usually define path schedules according to their cost—as specified by some routing metric—and packet importance [10, 16, 19, 41, 50, 64, 71]. Data packets also can be classified as less important than video packets [15]. In addition, video packets can be prioritized according to the type of frames or layers generated by video coding at the application layer. In this

Table 5 Summary of prior work according to their approach to multipath routing

References	Routing discovery	Multipath selection	Routing metric
[14, 18]	Proactive	Disjoint paths	QoS
[43]	Proactive	Partially disjoint	
[10, 34, 56, 57]	Proactive	Multi-interface	
[12, 14, 44, 47, 63, 71]	Reactive	Disjoint paths	
[48]	Hybrid	Multi-interface	
[28, 49]	Controller-based	Partially disjoint	
[30, 31]	Controller-based	Multi-interface	QoE
[64]	Proactive	Partially disjoint	QoS, Energy
[15, 19, 35, 36, 44]	Reactive	Disjoint paths	
[16]	Hybrid	Disjoint paths	
[73]	Proactive	Partially paths	QoS, interference
[41]	Reactive	Disjoint paths	
[37, 38, 82]	Proactive	Partially disjoint	QoE, interference
[51, 53, 54]	Hybrid	Disjoint paths	QoS, geographical, interference, energy
[50, 52]	Reactive	Disjoint paths	QoS, geographical, energy
[45]	Reactive	Partially disjoint	
[27]	Reactive	Partially disjoint	QoS, energy, interference
[17]	Hybrid	Partially disjoint	
[62]	Reactive	Disjoint paths	QoS, QoE, geographical, interference
[68]	Reactive	Disjoint paths	QoS, QoE, geographical, energy

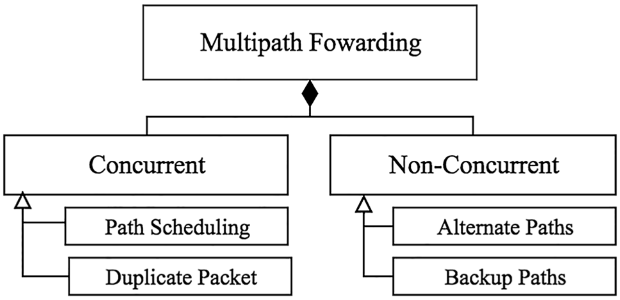


Fig. 8 Classification of multipath forwarding strategies

case, some studies have proposed a cross-layer design that checks the type of each packet and the current network conditions to ensure the transmission of the prioritized packets [17, 23, 33, 38, 52–54]. In general, these studies assume a fixed amount of a maximum of three types of packets, regardless of the capacity of the paths. However, it can be impractical when there are not enough paths for all the types of packets.

When the capacity of the main path alone is not enough to forward the whole video stream, the packets can be decomposed, so that each flow matches the capacity of the available paths. Thet et al. [28] present a splitting method for video streaming over multiple concurrent paths to decompose the packet rate to match the capacity of available paths. This method can be applied in multipath video transmission; however, it is not recommended when the main path capacity already suffices to forward the whole video stream. In addition, it does not consider that path capacity can vary over time.

8.1.2 Duplicate packet

A simple approach to increase the reliability of video delivery is to duplicate video frame packets to forward over different paths. Hence, copies of the same packet are transmitted over selected paths [44, 60]. However, this creates redundant packets that can occupy useful bandwidth. Moreover, to generate duplicate packets at the source and to filter out these duplicate packets at the destination, a special arrangement is required. For example, two agents are used in [60]: one to generate duplicate packets at the transmitter and another to filter received duplicates. Although it provides error resilient video transmission, it can overload the network.

8.2 Non-concurrent multipath forwarding

This strategy has been presented in the literature to improve the reliability of video transmission using alternative paths. As illustrated in the taxonomy of Fig. 8, studies have proposed the use of backup paths and alternate paths as non-concurrent forwarding approaches. These approaches seek to provide fault-tolerance and load-balancing, respectively.

Table 6 Multipath classification of the proposals for wireless multipath video transmission found on the literature according to the characteristics of their forwarding mechanisms found on the literature

References	Multipath forwarding	Mechanism
[10, 15–17, 19, 28, 33, 37, 38, 41, 47, 50–54, 64, 71]	Concurrent	Path Scheduling
[44, 60, 82]	Concurrent	Duplicate packet
[45, 49, 62]	Non-concurrent	Backup paths
[12, 47, 48, 64]	Non-concurrent	Alternate paths

8.2.1 Backup paths

It is one of the most popular multipath forwarding techniques to provide fault-tolerance. In general, the idea is to use only a path for packet forwarding, while keeping some alternative paths ready to use in case of necessity. For example, if a path fails because of a broken link, then packets can be retransmitted through another path. In general, fault-tolerance approaches select two paths, so that whenever the primary path fails, the transmission falls back to the secondary path [45, 49, 62].

8.2.2 Alternate paths

This strategies exploit multiple paths to achieve a better distribution of traffic and to provide load-balancing. Some studies have used these strategies to balance energy consumption among network nodes [47, 64]. They propose different models that perceive the path load and node energy consumption and, accordingly, control the packet forwarding.

A weighted round-robin scheduling policy strategy can be a simple and effective alternative to distribute video traffic. This strategy was implemented in [12, 47] in which the traffic flows are forwarded proportionally over alternate paths. Furthermore, Wu et al. [48] propose a multipath forwarding mechanism that implements a packet distribution based on the path quality to adjust video traffic load and minimize total distortion.

8.3 Summary

Table 6 summarizes the different multipath forwarding strategies found in the literature to optimize the multipath video transmission.

Multipath forwarding is one of the mechanisms that presents the most promising strategies for multipath video transmission. The literature has contemplated interesting alternatives, mainly with regard to concurrent paths, which is the focus of this survey. In this case, we can notice most studies have focused on path scheduling, where there are still many challenges to implementing an ideal mechanism to forward video packets over multipath while still considering video coding techniques from IoT application aspects.

9 Conclusion

Wireless multipath video transmission has attracted the attention of several researchers as a strategy to improve the quality-of-service and reliability of video services. This paper has presented a systematic survey that aims to organize recent studies to provide direction for future research. For this, we introduced a component-based taxonomy that comprise wireless multipath video transmission systems. A quick overview of those components was presented and the different approaches found in the literature were discussed and summarized.

The development of efficient applications for wireless multipath video transmission continues to be an open area that is promising for future research. Therefore, we have organized the key components that have demanded more investigation, thus encouraging the proposal of new approaches.

There is great research potential for implementing cross-layer support in IoT application scenarios. In this survey, for instance, we identified several studies that jointly tackle video coding and multipath routing protocols. Cross-layer design approaches have demonstrated the benefits of making multipath forwarding decisions according to video coding. In this direction, there has been a trend for future research on wireless multipath video transmission, especially for issues of the strategies to forward packets following the cross-layer design between application and network layers.

Finally, we also identified open challenges about routing metrics for multipath selection. As an example, depending on the routing metric, the capacity of multi-hop wireless networks might be saturated by increasing the number of hops. Thus, it can be necessary to investigate metrics that have a global view of the network as well as consider the multiple sources of transmission demanded by video services.

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