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A Survey on Multicast Communications in Multi-hop Wireless Networks

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Abstract

Performance-guaranteed multicast in multi-hop wireless networks is a challenging issue due to complex interference, high power consumption, node mobility, and limited multicast capacity. Although a lot of research efforts have been put into developing strategies for addressing these challenges, a survey of multicast communications in multi-hop wireless networks is lacking. This paper aims to provide in-depth insights into this research area by identifying unique challenges that have made performance-guaranteed multi-hop wireless multicasting a tough task, and by using these challenges as metrics to evaluate existing strategies including channel allocation, scheduling transmissions, utilization of external communication resources, mobile multicasting, and energy efficiency. We also discuss remaining challenges and emerging topics that have the potential to enhance multicast performance, and hope this can help researchers efficiently find new research directions.

Keywords:

multi-hop wireless networks, multicast, multicast performance

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1. Introduction

Multicast is a form of one-to-many or many-to-many transmissions which enables the source to send a single packet to a group of receivers simultaneously. In this way, multicasting not only greatly reduces network traffic but also subsequently optimizes bandwidth. The concept of IP multicast was first introduced by Steve Deering [1] in the late 1980s, and then the deployment on the Internet, known as the Multicast Backbone (MBONE), began in the early 1990s. IP multicast relies on multicast-capable IP routers to deliver a single packet to multiple receivers and therefore resulting in deployment limitation. To overcome this issue, application-layer multicast [2, 3, 4, 5] has been proposed as an alternative solution. The notion of application-layer multicast is to construct an overlay multicast network on top of the underlying physical network and use the overlay network for packets transmission. As a result, packet replication happens at end hosts rather than network routers.

With the increasing popularity of wireless and mobile devices (e.g., laptops, smartphones, tablets), a large number of studies have been conducted to find solutions to support multicast communications in wireless networks. Unlike wired multicast, due to the broadcast nature of the wireless medium (resulting in a well-known property - wireless broadcast advantage (WBA)), a single transmission from a wireless node can be received by multiple neighbouring receivers that are within its transmission range. A major difference between wireless broadcast and wireless multicast is that instead of sending a packet to all nearby receivers, multicast only sends it to intended receivers. This brings a lot of advantages including improving the network resources' utilization, minimizing the power consumption, and in turn increasing the network's throughput and lifetime.

In general, wireless networks can be classified into single-hop and multi-hop wireless networks. A single-hop wireless network (e.g., traditional cellular networks) transmits packets from a sender to a receiver via one hop, whereas a multi-hop wireless network (e.g., wireless sensor networks, wireless mesh networks) connects a sender to a receiver through a multi-hop wireless link. Multicast communications in a multi-hop wireless network are more challenging than in a single-hop network due to complex interference, high power consumption, node mobility, and limited multicast capacity. In addition, multi-hop wireless networks are regarded as a fundamental technology for many emerging applications such as the Internet of Things (IoT), vehicle networks, aerial networks, etc. Hence, the focus of this paper will be on multicast communications in multi-hop wireless networks. More specifically, after analyzing the challenges faced by multi-hop wireless multicasting, we present a survey of existing multicast strategies including channel allocation, scheduling transmissions, utilization of external communication resources, mobile multicasting, and energy efficiency. Through the discussion of how existing studies attempt to address these challenges, we are able to share our insights regarding state-of-the-art technology as well as emerging topics that deserve further study. Our goal is to increase the research efficiency for those researchers who are interested in this field, as well as help them efficiently find new research directions.

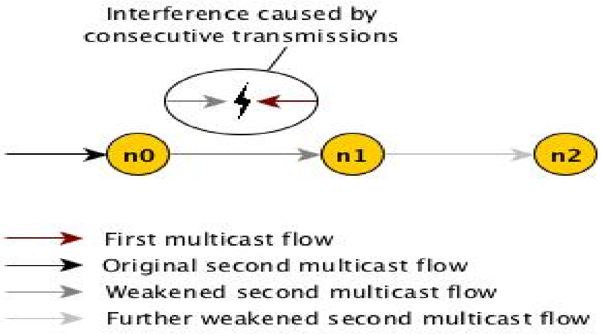
The rest of the paper is organized as follows. Section 2 discusses the challenges of deploying performance-guaranteed multicast service in multi-hop wireless networks. Section 3 provides a comprehensive overview of major strategies that address the aforementioned challenges. Section 4 discusses emerging topics and research directions. Finally, we conclude the paper in section 5.

2. Challenges of Multicast in Multi-hop Wireless Networks

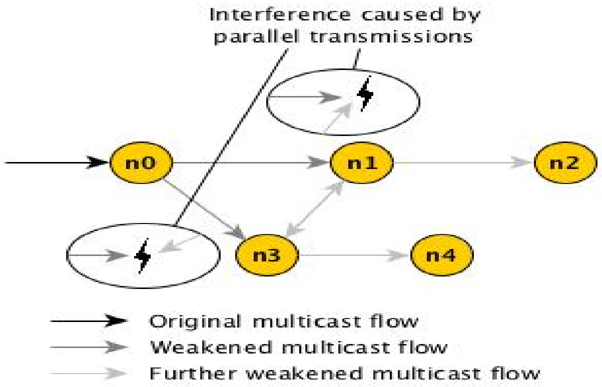
Multi-hop wireless networks can be either static or mobile. Static multi-hop wireless networks are composed of static wireless nodes such as routers, gateways, access point (APs), and end devices, whereas in mobile multi-hop wireless networks, wireless nodes often change their location within network. The major challenges of multi-hop wireless multicasting can be described as follows:

2.1 Complex Interference

The wireless transmission medium is openly accessible. The simultaneous submissions from nearby nodes interfere with each other if the submissions use the same channels. When it comes to multicast, as Tu analyzed in [6], interference becomes more complex mainly due to consecutive transmissions on the same multi-hop paths (as shown in Fig. 1 (a)) and parallel delivery of multicast data on paths that contain at least one interfering hop (as shown in Fig. 1 (b)). In Fig. 1 (a), when n0 sends multicast traffic to n1, n1 is forwarding data received from n0 to n2. Due to the broadcast nature of the wireless medium as shown in the circle, the transmission n1→n2 competes with the transmission n0→n1 that occupies the same channel, which degrades the multicast performance at both n1 and n2. In Fig. 1 (b), suppose n1 and n3 are the multicasting forwarders and they are within each other's interference range. When data is multicasted to n2 via the path n0→n1→n2, the transmission n0→n3→n4 takes place in parallel. Such parallel transmissions cause interference that further degrades the performance at n1 and n2.



(a)



(b)

Figure 1: ***An example of multicast interference caused by consecutive (a) or parallel (b) transmissions.***

The combined performance degradation caused by such complex interference pattern can be more severe when multicasting multimedia data or data with low signal strength. This is because multimedia data has high transmission rates which lead to more intensive interference. For transmitting data with low signal strength, it can happen after a few hops of forwarding via a multi-hop path. For example, two teams of PC gamers are competing against each other in the same district, and each team subscribes to one multicast group. A large number of concurrent, parallel and high rate data transmissions are generated throughout the game, which will severely influence the perceived video quality at the receiving end. At worst, it can lead to terrible lag and massive packet loss that makes the game virtually unplayable. Hence, how to effectively suppress multicasting interference is crucial for high-performance multi-hop wireless multicasting.

In addition, the control traffic caused by establishing or maintaining multicast architectures requires occupying channels which may conflict with normal data transmission on the same channels. According to Ruiz et al. [7] and Liu et al. [8], the minimizing interference of multicast trees is an NP-hard problem. Meanwhile, the radio frequency bands 2.4GHz and 5GHz used by most commercial Wi-Fi devices are accessible by many other non Wi-Fi related appliances, which puts more interfering signals to wireless multicast.

2.2 High Power Consumption

A large number of wireless devices, such as IoT devices or personal mobile devices, are battery-powered. Some of them may not be feasible to recharge as they are often deployed in large/remote areas or embedded into structures (e.g., buildings, roads). Therefore, multicast communications should be implemented in such a way that energy consumption can be minimized in order to prolong the node lifetime. However, in multicast communications, the maintenance of multicast architecture is more complicated than unicast or broadcast. As such, frequent control packet exchange is required between multicast forwarders, which not only consumes the energy of these forwarders but also causes interference on the employed wireless links. These issues become more severe when multicast members are mobile as additional control packets need to be exchanged in order to maintain the network topology.

Moreover, due to the broadcast nature of the wireless medium, multicast packets continue to unnecessarily wake up within-range clients operating in power-save mode (PSM) to receive packets, even if they are not subscribed to any multicast group. This issue is particularly worth considering for devices that are close to multiple multicast forwarders.

2.3 Node Mobility

Mobility in a multi-hop wireless network requires routing paths to be updated in time to avoid inaccurate routing or packet loss. Group communications with fast mobile members attract much attention in the past decade due to the fast development of high-speed trains and vehicles (e.g., The maximum operating speed of electric trains in New Zealand is 110 km/hr). As such, efficient group membership management is crucial for mobile multicasting. For multimedia communications with interactive mobile users, real-time handoff schemes in a multicasting context are important for accurate and effective communications.

Furthermore, in mobile multicasting, due to the unpredictable node movement, it is difficult to understand the network condition associated with nodes during their movement. As a result, it is difficult to achieve performance-guaranteed multicast for these mobile nodes. This brings us a lot of challenges to design a multicast scheme to meet different group members' performance perspective.

2.4 Limited Multicast Capacity

Multicast is designed for efficient group communications. Group communications often contain multimedia transmission which requires sufficient bandwidth due to its high transmission rates. It is well known that commercial wireless communications using certain RF bands provide limited bandwidth. For multicast, the broadcast nature of the wireless medium spreads data widely to those nodes that may not belong to any multicast group. As limited wireless bandwidth is unnecessarily used, it is necessary to selectively choose multicast forwarders to avoid bandwidth wastage.

In mobile communications, Chiang et al. [9] found that routing table updates alone can consume near half of the bandwidth even under medium mobility level. For multicast, such routing table updates need to involve more forwarders than unicast or broadcast due to the selective establishment of multicast architectures.

3. Major Strategies Designed for Multi-hop Wireless Multicasting

To address these challenges, a number of strategies have been proposed by the researchers including channel allocation, transmission scheduling, additional resources exploiting, energy efficiency, and seamless mobile transition.

3.1 Channel Allocation in Multi-hop Wireless Multicasting

Early multicast studies focused on single-channel transmissions [7, 10, 11]. These solutions experience severe performance degradation due to the complex interference we discussed in the previous section. Studies [12, 13] showed that by exploiting partially overlapped channels appropriately, data can be transmitted through these channels simultaneously with acceptable performance. Hence, later studies mostly investigated the use of Multi-Radio Multi-Channel (MRMC) to enhance multicast performance.

Wireless multicast strategies that use multiple channels can be classified as centralized multicast and distributed multicast. In centralized multi-channel multicast, a central controller termed Base Station (BS) collects information from all other nodes to form a global knowledge. Based on the overall network topology, BS establishes a multicast tree and then manages channel assignment. Liu et al. [8] proved the Minimum Cost Multicast Tree (MCMT) problem in MRMC WMNs is NP-hard. Based on this theorem, they proposed a polynomial-time near-optimal algorithm Wireless Closest Terminal Branching (WCTB) to solve this problem. WCTB uses Dijkstra's algorithm to compute the minimum cost from the source to each receiver. To alleviate the interference between multicast trees, they proposed Minimum Interference Minimum Cost Routing (MIMCR) to compute the minimum interference minimum cost path between source and receivers. As path cost and co-channel interference of a path are two additive metrics and finding an optimal path with two additive metrics is NP-complete, their algorithm gives priority to transmission cost. Cheng et al. [14] addressed that a joint solution is better as it solves QoS multicast routing and channel assignment in a conjoint way. In their work, it first uses a fixed channel assignment strategy to assign channels and then evaluates it by the total channel conflict and tree cost. Three path finding algorithms they proposed are based on different intelligent computational methods including genetic algorithm, simulated annealing, and tabu search. These algorithms are applied separately in order to discover delay-bounded minimum-interference low-cost multicast trees.

Centralized channel assignment schemes are simple and generate less traffic overhead. However, they suffer from a single point of failure as well as heavy workloads on the central nodes. Therefore, studies on distributed channel assignment schemes have been carried out. In general, these schemes allocate channel in a distributed manner, wherein each node has local knowledge of its neighbours via periodic message exchange. Zeng et al. [15] proposed a Multi-channel Multicast (MCM) algorithm aiming to improve the throughput. A multicast tree based on Breadth First Search (BFS) is first built to minimize total hop count distances between source and receivers. After that, two reducing interference strategies are used by each node to decide the channels: 1) Ascending channel allocation ascendingly assigns the channels to the interfaces of tree nodes until it reaches the maximum channel number, and then starts from channel 0 again. 2) Heuristic channel assignment heuristically assigns channels to different interfaces in order to minimize the sum of the interference area of all the transmissions. The learning automata based multicast routing (LAMR) [16] is another distributed channel assignment scheme that addresses the NP problem of allocating channels with minimum interference. To start, learning automata (LA) resides on interfaces of each node across the network. Based on the action probability vector, each LA selects an action that specifies which channel it should use in order to minimize interference. In detail, when LAMR constructs a multicasting tree, it includes a TTL and a learning rule in its control messages. These messages allow each node to find its shortest delay path to the multicasting sender, which incurs the update of the action probability vector. Once the initial multicast tree is constructed, nodes on the tree will optimize the tree structure based on the information in LAs.

3.2 Scheduling Transmissions in Multi-hop Wireless Multicasting

The performance of channel allocation schemes heavily relies on the number of available non-overlapping channels which is however limited in the radio frequency band. This has motivated research efforts on making efficient use of single channels. Scheduling is a well-studied strategy for this purpose.

In [17], multiple multicasting flows are scheduled based on time slots and in a round-robin fashion. Time slots assigned for different multicasting flows are derived based on flow transmission rates, the number of flows, channel capacity, and the end-to-end performance requirements. Network calculus is used as the mathematical tool to obtain the formulas of time slots for different flows. This study finds that by scheduling flows, a channel can admit more traffic even when the channel is considered to be “saturated” by conventional transmission methods. In addition, the work proposes a channel aggregation policy that accumulates the residual capacities (after scheduling) for useful multicasting resources. Cao et al. [18] proposed a cross-layer scheduling and routing scheme to assign multiple channels in multi-hop wireless networks. This scheduling scheme extends the distributed maximal scheduling in traditional single-channel wireless networks into tuple-based multi-channel wireless networks. A distributed delay-aware routing algorithm is developed based on the Lyapunov optimization method and the minimum-consensus algorithm, minimizing the end-to-end delay for each flow while meeting the constraints of the routing optimization problem in a distributed manner. The delay minimization and priority scheduling in [19] uses a resource contention graph to minimize delays. In order to achieve an optimal topology graph, linear programming is employed.

In addition to multiple channel scheduling, multiple transmission rates are also scheduled in the literature in order to achieve high QoS performance. Qadir et al. [20] compared a few channel assignment algorithms with multiple rate adaptation for multi-hop wireless broadcasting. Their study focused on decreasing delays by adaptively scheduling the rates at different nodes. Farzinvash et al. [21] proposed multi-gateway multi-rate multicast routing (MGMR) to maximize the network throughput while preserving fairness between receivers. In their algorithm, less-loaded channels are assigned to the end node of each multicast tree branch as it is prone to more interference. In this way, interferences are balanced throughout the network and in turn, more room is available for the receivers to determine the obtained data rates for maximizing network throughput. Tu [6, 22] claimed that these two approaches are not suitable for multimedia communications due to potential bottleneck nodes that may be caused by parallel high-rate transmissions. To balance the tradeoff between network throughput and transmission coverage, a parallel low-rate transmission (PLT) scheme is introduced. The notion of this scheme is to transmit a multimedia stream together at the same rate because the aggregation of multiple low-rate channels can produce higher throughput across greater distances. Based on PLT, an advanced algorithm alternative rate transmission (ART) is proposed. In order to reduce the number of required orthogonal channels, ART controls interference caused by consecutive or parallel multicast transmissions (mentioned in Fig. 1) by precisely assigning regular and PLT roles to multicast nodes. Finally, the link-controlled multi-rate multi-channel protocol is developed for transmitting multicast multimedia traffic across much larger areas.

3.3 Utilization of External Communication Resources

Channel allocation and transmission scheduling are two strategies that make full use of unlicensed wireless resources. As unlicensed wireless resources are limited, a line of studies explore networking resources outside of the unlicensed RF band. These studies can be classified as utilizing licensed RF band to multicast data and combining wired bandwidth to multicast data.

Cognitive Radio Networks (CRNs) has been regarded as a promising technology to achieve better utilization of radio resources in terms of primary/secondary network setting. As multicast needs to transmit one source to a group of receivers, unique challenges in multicast over multi-hop cognitive mesh networks includes the heterogeneity of availability and unpredictable primary occupancy among secondary users of one multicast group. Therefore, the design factors of multicasting in such networks should focus on spectrum sensing and dynamic spectrum access. Hu et al. [23] propose a cross-layer optimization approach based on the conclusion that multicasting in CRNs is a formulated mixed nonlinear integer programming (MNLIP) optimization problem. They use sequential fixing (SF) algorithm and greedy algorithm to divide the enhancement layer of FGS video data into multiple sub-layers with different rates and modulation-coding (MC) schemes. Then, a tile scheduling algorithm TSA to assign video packets to available channels. Qu et al. [24] proposed a network-coding-based multicast approach. It first formulates the multicast problem under uncertain spectrum availability as a chance-constrained program. A two-dimensional conflict graph is constructed to encapsulate both hyperarc scheduling and channel selection into hyperarc-channel tuples. Then, an efficient distributed algorithm is introduced to simultaneously optimize the flow rate and coding subgraph with channel selection.

For utilizing wired bandwidth to multicast data, studies employ Internet links to connect gateways together which hold great potential to reduce interference and signal loss caused by wireless transmissions. In this way, it extends the performance-guaranteed wireless transmission distance. In detail, Farzinvash et al [21] discussed how to select gateways for the purpose of efficiently using Internet links. A gateway with a more number of receivers will be selected with priority because it may reduce more interference by connecting a more number of receivers to other wireless nodes via Internet links. Karimi et al. [25] presented a cross-layer design to jointly select appropriate channels for each node and optimally determine the assignment of multimedia flows to multiple cooperative gateways in order to maximize throughput. They applied the classic Lagrange relaxation technique and an iterative primal-dual optimization algorithm that iteratively switches between solving primal sub-problems for channel allocation and routing. Tu et al. [26] introduced a hybrid wired-wireless routing hierarchy that can judiciously employ wired Internet shortcuts, making it an efficient solution for high data rate and large-scale multicasting. This hybrid hierarchy consists of several algorithms: the access area formation algorithm divides wireless nodes into clusters and nodes from the same clusters can communicate wirelessly with guaranteed performance; the weighted gateway uploading algorithm selects gateways that can produce short-delay and load-balancing performance to connect wireless nodes to the Internet links; the link-controlled routing tree algorithm decreases multicast interference constructing a multicast tree with the least number of forwarders in each access area; the dynamic group management (DGM) algorithm maintains low control overhead when membership changes. Yuan et al. [27] proposed the gateway assisted multicast algorithm towards low latency which aims at minimizing delays for video transmissions. When building multicast trees, the links with the best bandwidth conditions will be chosen by using the bandwidth prediction model to shorten delays. Gateways then act as group leaders to maintain multicast group membership. Since these gateways can see the local and global information of network topology and bandwidth, they can select routing paths more properly to minimize delays.

3.4 Mobile Multicasting in Multi-hop Wireless Networks

A key role in designing multicast protocols for mobile wireless networks is to provide robust routing as the network topology changes frequently and arbitrarily. Tree-based and mesh-based multicast routing are well-established concepts in wired networks. Researchers have extended these two schemes to develop several multicast protocols for mobile wireless networks. Apparently, efficient network topology maintenance is critical for mobile multicasting. Both approaches require extra control packets flooding in order to make each node to be aware of the current topology.

In tree-based approach, a multicast tree is composed of unique paths from each end-host to its child members which to be used to deliver multicast traffic. Wu et al. [28] proposed ad hoc multicast routing protocol utilizing Increasing id-numbers (AMRIS), which dynamically assigns an ID number to each node in each multicast session. Each multicast tree is rooted at a special node having the smallest-id. The id number increases as the tree expand from the smallest-id. Each node is required to broadcast beacons containing the id and other membership status information to its neighbours to keep track of the topology. Royer et al extended AODV to multicast operation, called MAODV [29]. The broadcast route discovery mechanism of MAODV is very similar to AODV, except that each message carries additional multicast group information. Also, similar to AODV, it relies on the group sequence number to guarantee that each node keeps a record of the freshest route table.

In mesh-based approach, every node has at least one connection to each of the other nodes. ODMRP introduced by Sung et al. [30] uses the forwarding group concept, with which only a subset of nodes forwards the multicast packets through shortest paths, to build a forwarding mesh for each multicast group. Unlike AMRIS/MAODV that build and maintain a multicast tree based on the hard-state information, ODMRP uses a soft-state on-demand approach for membership maintenance. More specifically, multicast routes are established and updated as needed via network wide floods and thus no explicit control packets need to be sent to join or leave the group. Different from these protocols, Aceves et al. proposed Core-Assisted Mesh Protocol (CAMP) [31] that is based on the concept of Core-based trees (CBT) from IP multicast. To join a multicast group, a receiver only sends unicast join requests towards a core node of the desired group. A routing scheme based on reverse shortest path problem and heartbeat messages is employed to use heartbeat messages and reverse shortest paths, ensuring that the topology contains all the reverse shortest path.

Generally, there is a tradeoff between efficiency and robustness: tree-based protocols provide higher transmission efficiency at the cost of lower robustness, whereas mesh-based protocols provide better robustness to topology changes at the cost of larger forwarding overheads. A hybrid solution may be worth exploring to combine the benefits of both schemes. Two typical hybrid approaches are AMRoute [32] and MCEDAR [33].

AM-Route is to create multicast mesh links using bidirectional tunnels connecting close group members, wherein a multicast distribution tree is established by using a subset of the available mesh links. MCEDAR creates an implicit source based forwarding tree meanwhile maintains an underlying mesh routing infrastructure.

3.5 Energy Efficiency in Multi-hop Wireless Multicasting

While energy consumption is a critical concern for wireless/mobile multicasting, traditional tree-based or mesh-based protocols require high processing power due to periodical network-wide floods during tree/mesh construction and maintenance. To overcome this issue, several stateless multicast protocols have been proposed. These protocols assume that every node in the network is aware of its own physical positions (by using GPS or a location-finding service) and thus flooding is no longer required. Multicasting is possible without explicitly building a tree/mesh. Other protocols also divide the network into several geographic regions for efficient routing. This approach significantly eases multicast group management by minimizing control overheads, which in turn reduces power consumption, increases bandwidth, and enhances network life span.

Ji et al. proposed differential destination multicast [34] to avoid state maintenance at nodes by concentrating on membership control at the data sources. A list of destination addresses is encoded in the header of each data packet that the source sends out to achieve self-routing. Sanchez et al. proposed geographic multicast routing (GMR) [35], which is a fully-localized algorithm that is solely based on local geographic information obtained from neighbouring nodes. In GMR, the cost over progress metric is used by the source to select the next hops towards destinations. The greedy set partition selection algorithm is used by each node to select one or more neighbours as relay nodes for a set of destination receivers. Also, merging subsets operations are used to improve progress. Although pure geographic multicast protocols such as GMR do not require creating and maintaining global routing structure, they may not be suitable for large-scale resource-constrained networks as they still generate significant encoding overhead including information about membership, location and so on when multicast group increases. Das et al. proposed HRPM [36] to solve this issue. HRPM is a hierarchical multicast protocol which recursively decomposes a network into multicast groups and then into subgroups of manageable size. Multicast group members agree upon a rendezvous point (RP) as the group manager and each subgroup is restrained by an access point (AP). To reduce the maintenance of AP and RP, geographic hashing that was previously designed for data storage in static sensor networks is also adopted. Furthermore, to ensure the stored location information is up-to-date in mobile wireless networks, HRPM extends geographic hashing via a continuous handoff process. Feng et al. [37] developed receiver-based multicast (RBMulticast) protocol which ensures that the relay node of packet transmission is decided by the potential receivers of the packet in a distributed manner. Due to the lack of knowledge of neighbour nodes and routing tables, it uses an imaginary destination termed virtual node as the packet destination. It divides the network into several multicast regions and calculates a virtual node location based on each group nodes' location. The node closest to the virtual node and having low expected number of hops value takes responsibility for forwarding the packet.

3.6 Discussion

In Table 1, we compare how efficient these five strategies are in addressing the challenges analyzed in Section 2. In Table 2, we further compare their achievable performance in terms of QoS-based metrics.

Table 1: ***Comparison of different multicast strategies based on challenges.***

Strategies	**Control interference**	**Controlling power consumption**	**Handle mobility**	**Increasing transmission capacity**
Channel allocation	Yes.	Not specifically. Complex allocation algorithms may consume considerable power resources.	Not specifically.	Yes. By reducing interference, capacity improves.
Transmission scheduling	Yes.	Not specifically.	Not specifically.	Yes. Reuse channels by scheduling enhances channel's utilization.
External resource exploitation	Yes.	Extra power can be consumed by cognitively detecting idle licensed channels.	Yes, if user mobility is taken into account.	Yes.
Mobility handoff	Yes.	May cause high power consumption.	Yes.	For mobile nodes.
Energy efficiency	Yes if controlling interference is a consideration.	Yes.	Most recent studies on energy efficiency take mobility into account.	Not specifically.

Table 2: ***Comparison of different multicast strategies based on achievable performance.***

Strategies	**Generated traffic overhead**	**Power consumption**	**Handle mobility**
Channel allocation	Low as compared to mobile handoff strategies.	Acceptable delays are achievable when non-overlapping channels are sufficient.	Throughput performance is improved as interference is decreased.
Transmission scheduling	Low as compared to mobile handoff strategies.	Acceptable delays are achievable when scheduling conditions meet.	Throughput performance is improved when scheduling conditions meet.
External resource exploitation	Low as compared to mobile handoff strategies.	Achieve better delay performance if external resources are available.	Achieve better throughput performance if external resources are available.
Mobility handoff	High overhead usually generated for smoothly transiting mobile nodes.	Average delays may be worse than other strategies due to the performance of mobile nodes.	Average throughput may be worse than other strategies due to the performance of mobile nodes.
Energy efficiency	Lower than other compared strategies.	Delays are achievable for low-rate applications.	Throughput performance is improved as overhead is decreased.

Tackling the challenge of controlling interference is usually the main motivation of channel allocations, transmission scheduling, and external resource exploitation strategy. Most of the mobility handoff schemes also attempt to avoid interference, especially focusing on those caused by temporary transition connections. A large number of schemes designed for energy efficiency are based on sensor networks that consist of various Internet-of-Things (IoT) devices. Low-cost IoT devices are generally not equipped with multiple radios and have limited power supplement, which affects the capability of these schemes to effectively avoid interference by using channel allocation, scheduling, or utilizing external communication resources.

To control power consumption, most schemes that apply channel allocations, scheduling, and external resources do not take power efficiency into account. As the studies on mobile or IoT multicasting are getting popular, energy efficiency has attracted a lot of research attention. However, in mobile multicasting, the tracking or updating mobility locations can consume additional energy that is unnecessary for all other strategies. Similar to the challenge of control power consumption, the challenge of smoothly handling mobile nodes in a multi-hop multicasting environment has been mostly studied by the strategies of mobility handoff and energy efficiency. However, channel allocations, scheduling, and external resource utilization are often employed as a part of strategies by mobile multicasting in multi-hop wireless networks.

As for increasing multicast transmission capability, with channel allocations, non-overlapping or low-overlapping channels are used to offer a larger accumulated capacity as well as reduce interference. Transmission scheduling makes use of each channel more efficiently by allowing each channel to contain more traffic flows or providing connections to more wireless nodes. The utilization of licensed RF bands or wired links greatly increases the multicasting capacity of multi-hop wireless networks and therefore it is a promising strategy that may make a difference to wireless transmission capacity. Studies on mobile handoff often explore the additional capacity to allow mobile nodes to be smoothly transited. The above three strategies are enhanced for working in a mobile environment. In general, increasing multicast capacity is not a major concern of energy efficiency studies.

For the traffic overhead, performance-guaranteed mobile multicasting generates more overhead traffic to the network than other compared strategies. This is because smooth transitions require additional communications between different multicast group members. For the achievable performance, the strategies of channel allocation, transmission scheduling, and extra resource utilization mostly focus on traditional networking data traffic or multimedia traffic flows. Their algorithms are mainly designed to utilize communication resources efficiently and guarantee the end-to-end performance of multimedia applications. Most energy efficiency schemes proposed for IoT devices usually generate data traffic with much lower transmission rates. Energy is used efficiently without violating the performance bounds of IoT applications. However, they may not be able to achieve acceptable performance for applications with high traffic rates.

Overall, different strategies can improve some of the performance metrics but not all. The selection of a multicast strategy heavily depends on the application requirements as well as constraints. On the other hand, there are still a number of remaining issues that deserve further research. For example, the coexistence of multicast and unicast transmissions, the performance consistency across group members, interference from other external factors, etc.

4. Emerging Topics of Multi-hop Wireless Multicasting

So far, much of the effort has been on developing strategies to cope with primary challenges as we addressed in section 2. However, with the increased number of Internet of Things (IoT) and Virtual Reality (VR) devices, multicast communication in multi-hop wireless networks is facing many new problems that deserve further investigation. Modern multi-hop wireless multicasting requires study efforts on the following topics:

4.1 QoE Guaranteed Multi-hop Wireless Multicasting

Quality of Experience (QoE) refers to the communication quality perceived by users. In modern networks, users connect to multi-hop wireless networks via various devices (e.g., phones with different display qualities) in different communication environments (e.g., offices, vehicles). As a result, they have different perspectives on acceptable communication quality. It is not trivial to meet different QoE requirements while efficiently utilizing communication resources for multicasting.

QoE-based video streaming in multi-hop wireless networks has attracted many research efforts (e.g., [38, 39, 40]) in the past decade. However, little has been done on investigating QoE in the context of multicast communications. An effective method that is able to determine not only QoE measurements but also the thresholds of these measurements is still under development. Meanwhile, for multicast communication in which different users have different perspectives, it is significantly difficult to achieve efficient resource utilization due to high computational complexity. Besides, as applications for mobile wireless sensor networks and mobile cognitive radio networks are getting popular recently, we can no longer assume nodes are static in such networks. Also, it is more challenging to make users satisfied with the quality of VR videos because they need much higher resolution than conventional videos. As above, it is essential to develop mechanisms to dynamically assign clients to available media quality levels. Park et al. [41] proposed a cross-layer optimization framework, which includes algorithms for user grouping, wireless-resource allocation, and tiled-video rate selections, to jointly optimize VR-video multicast systems of reasonable complexity. In recent years, it has been shown that machine learning can successfully solve problems and enable automation in diverse domains. Machine learning also has the potential to be applied to multicasting. In fact, machine learning-based multicasting was first studied by Sun et al. [42] almost 20 years ago. Since then, researchers have proposed several reinforcement learning solutions by applying machine learning techniques such as learning automata [16, 43] to model routing in different types of multi-hop wireless networks. However, these studies are not related to QoE. In [44], a data-driven QoE management framework is designed to manage the performance perspectives of different IoT devices based on machine learning results. Modules to determine QoE measurements and structure multicast connections can be integrated into this framework for potential solutions for QoE guaranteed multi-hop wireless multicasting.

4.2. SDN-based Multi-hop Wireless Multicasting

Software-defined networking (SDN) provides multicast with the possibility of minimizing overall resource consumption while meeting different QoS constraints in a large-scale network. This is because SDN decouples network control plane from the data forwarding plane and the centralized control plane is able to provide a global view of network connections.

Most of the studies on SDN-based multicasting focus on either wired networks [45, 46] or data center management [47, 48]. The well-acknowledged SDN protocol OpenFlow was designed for static networks, lacking the capability to handle multicasting to mobile users.

Moreover, the control messages generated by OpenFlow have large sizes, making the protocol unsuitable for resource constrained wireless links or mobile devices. SDN-based multicasting has been studied for single-hop wireless networks (e.g., cellular networks [49]), with few tackling the challenges of multi-hop wireless networks. Among these studies on multi-hop wireless networks [50, 51], to the best of our knowledge, multicast is not specifically studied. Existing strategies (mentioned in Section 3) may be further developed for SDN controllers to carry out high-performance multi-hop wireless multicasting. Obviously, carrying out more strategies can make the most of network resources but increase the complexity at the same time. Machine learning techniques may also be developed to enable SDN controllers to learn network topologies or conditions in a resource-efficient manner, and thus make accurate control decisions for multi-hop wireless multicasting.

4.3 Secured Multi-hop Wireless Multicasting

Security is a primary concern of multi-hop wireless multicasting. Due to the broadcast nature of the wireless medium, nodes under multi-hop wireless multicasting are highly vulnerable to malicious attacks. Furthermore, with the rapid development of IoT and VR industry in recent years, network devices have become more diverse and carry more personal data, which has brought more challenges to provide secure multicasting in IoT environment. IETF has published a series of security policies and standards (e.g., [52, 53, 54, 55, 56]) for IP multicast. Unfortunately, they are not designed to a specific Internet standard of any kind, and most of them are based on conventional IP Multicast in the early years. Meanwhile, a number of security schemes [57, 58, 59, 60, 61] for multi-hop wireless communications have also been proposed in the literature. These schemes mainly focus on security concerns such as solving the issues related to authentication, key management and access control, without implementing in-depth investigations regarding the aforementioned challenges. Efficient integrating the strategies introduced in Section 3 with existing security schemes will be an interesting research topic.This paper reviews major strategies proposed for enhancing the performance of multicast communications in multi-hop wireless networks. We do not develop secured multi-hop wireless multicasting in further detail. For those readers who are interested in multicast security, they can refer to [62, 63] for further study.

5. Conclusion

This paper presented a survey of studies on multi-hop wireless multicasting. We first explored the major challenges faced by multicast in multi-hop wireless networks. It can be concluded that complex interference, high power consumption, node mobility, and limited multicast capacity are the major challenges. We then provide a comparison study of different multicast strategies to address these challenges. For each strategy, we have summarized the notion, introduced some major protocols/algorithms, and discussed the drawbacks. It has shown that channel allocation, scheduling transmissions, utilization of external communication resources, mobile multicasting, and energy efficiency strategies can greatly improve multicast performance by eliminating the aforementioned problems. Also, we addressed that there are still many challenges remain in existing solutions. Finally, we represented emerging research topics that deserve further attention in order to enhance multicast performance for further applications. We found that ML and SDN have provided more possibilities and alternatives to develop better multicast solutions. Still, they bring new challenges at the same time.

Overall, we believe that multicast communications is a rapidly growing and evolving research area. Multicasting applications and technology will surely play an important role in future-generation networks.

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