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Masterarbeit

Evaluation of medium-sized networks based on an original implementation of the MEADcast Router

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Hiermit versichere ich, dass ich die vorliegende Masterarbeit selbständig verfasst und keine anderen als die angegebenen Quellen und Hilfsmittel verwendet habe.

München, den 7. Juli 2077

. . . .

(Unterschrift des Kandidaten)

Abstract

Hier steht eine kurze Zusammenfassung der Arbeit. Sie darf auf gar keinen Fall länger als eine Seite sein, ca. eine drittel bis eine halbe Seite ist optimal.

Contents

1 Introduction

1.1 Motivation

Over the last two decades, the number of people with access to the internet has continuously increased at a rate of 5%, resulting in a current total of over 5 billion individual internet users [ITU23]. Furthermore, the unrelenting demand for data has led to an average growth in total bandwidth usage of 30% over the past five years. This development was further accelerated by the COVID-19 pandemic, as the increased reliance on remote work, online education, and digital entertainment surged the bandwidth consumption [Car21]. These growth rates are expected to remain high in the future. Especially Multimedia content like Video Streams, Conferences, and Online Games depict a major portion of the global internet traffic. Video traffic is accountable for more than half of the bandwidth consumed in 2020 [Car21]. Network Operators and Service Providers need to comply with the continuously rising demand.

Already in the late 1980s, Deering and Cheriton proposed a multicast extension to the IP protocol, to facilitate efficient multipoint communication (*1:m, m:n*) [DC90; Dee89]. Multicast offers the advantage, to greatly reduce the occupied bandwidth by condensing identical traffic into a single stream, targeted towards multiple recipients [Cai+02]. Routers may replicate packets of that stream at points where the paths towards the receivers diverge. Many of today's internet services, particularly those with high bandwidth demands, may benefit significantly from multicast delivery [RES06; TD18]. Besides technical benefits, the adoption of multicast communication could reduce the emissions caused by Communication Technology (CT). Several studies assert that networks are accountable for a major portion of today's CT emissions [AE15]. Furthermore, they forecast strongly increasing energy consumption by networks until 2030. Multicast communication has the potential to lower energy consumption and therefore emissions by promoting more efficient use of network resources and potentially reducing the need for additional infrastructure.

1.2 Challenges of Multicast

The application of IP-Multicast has yielded mixed results. Practically all of today's devices support IP-Multicast [RES06]. Furthermore, it is utilized on a local scale, and various protocols like IPv6 Neighbor Discovery [Sim+07], RIPv2 [Mal98], OSPF [Moy98] and mDNS [CK13] rely on multicast.

However, more than thirty years since the initial proposal of IP-Multicast, its global deployment and usage still lags far behind expectations [Dio+00; RES06]. Despite the potential advantages of Multicast, the majority of internet traffic continues to rely on point-to-point communication, known as *unicast* [Zha+06]. There are several reasons for the limited usage of IP-Multicast.

Feasibility Besides the aforementioned advantages, IP-Multicast entails various technical obstacles. Compared to unicast, it exhibits increased technical complexity, requiring the interaction of various protocols on multiple network layers [RES06; Dio+00]. Furthermore, multipoint communication in general interferes with the application of today's widespread security mechanisms like encryption [RH03]. Moreover, IP-Multicast is based on a fixed address space [Dee89; DH06], which has an insufficient number of addresses. This limitation makes it infeasible to map highly dynamic sessions, like conferences, onto this space [DT19]. Additionally, the protocol involves a complex routing procedure, which requires all routers along the path to maintain a per-session state [Dio+00; RES06]. Consequently, global IP-Multicast availability is constrained, as successful packet delivery necessitates all routers to support the protocol. However, this scenario is unlikely since many commercial routers come preconfigured with IP-Multicast disabled [Aru19]. Moreover, the following paragraph describes, why Network Operators are probably not willing to enable it.

Desirability So far, Network Operators and Internet Service Providers (ISPs) have shown limited efforts to deploy Multicast within their Administrative Domains [Dio+00; RES06; ST02]. The increased technical complexity of Multicast requires more extensive management efforts. Additionally, due to the complex routing procedure, infrastructure upgrades may be necessary. Despite its potential for significant bandwidth savings, ISPs seem to assess the deployment of IP-Multicast as an unsuitable investment [RES06]. Another reason is the more complex pricing model of multipoint communication. Charging for multicast services is non-trivial compared to existing unicast billing [RES06]. On top of that, IP-Multicast hampers Network Operators' ability to anticipate network load. Forecasting the number of replicas generated from a multicast packet, entering the Network Operators Administrative Domain, is unfeasible [Dio+00]. Combined with the limited security mechanisms of IP-Multicast, this represents a vulnerability, potentially exploited for amplification attacks. This fact makes intra-domain IP-Multicast even more unlikely.

Unless ISPs face pressure to expand their service offering, increasing multicast deployment is doubtful. As multicast delivery has no direct impact on receivers, customers are not expected to exert the necessary pressure. Moreover, statistics illustrate that more than half of the internet traffic volume is HTTP-based [Clo23], which is not well suited for multipoint communication. Additionally the usage of Multicast is discouraged by web browsers, the most widely utilized HTTP clients, due to their technical limitation to TCP/HTTP[1].

1.3 Goal and Contribution

The current state of the internet put forth various unicast-based alternatives, aimed at addressing the absence of a globally usable multicast protocol [Zha+06]. One such alternative, known as MEADcast [TD18], offers the capability for 1:n sender-based IPv6 multipoint communication over the internet [DT19]. Key features of MEADcast include the preservation of receiver privacy, technology-agnostic destinations, and zero network support requirements.

Building upon prior research conducted by Danciu and Tran [DT19], the primary goal of this thesis is to conduct a real-world evaluation of MEADcast, utilizing a Linux Kernel

[1]Despite the growing popularity and browser support for QUIC [IET21; JC20], also known as HTTP over UDP, it encounters similar challenges as TCP/HTTPS. This include issues such as packet acknowledgment and the client side generation of random numbers [IT21].

implementation of the required router software. This step represents a logical progression from earlier investigations of MEADcast, which were based on network simulations [TD18] and Software-defined networking (SDN) [Ngu19]. The evaluation primarily focuses on the following aspects:

Feasibility Study The first part of the evaluation assesses the feasibility of deploying MEADcast in a network. This aims to identify potential limitations and structural issues of the current protocol specification. Further investigation examines the practicality of using MEADcast on the internet, taking into consideration concerns related to IPv6 extension header processing [Gon+16].

Performance Evaluation A comparative performance analysis is conducted to evaluate MEADcast in comparison to both IP unicast and multicast. This assessment provides insights into the efficiency and effectiveness of MEADcast as a multipoint communication solution.

Scenario identification Building on the results of the previous evaluation steps, this phase involves identifying scenarios, application categories, and characteristics that justify the utilization of MEADcast. Thereby, it can be determined where MEADcast may offer advantages and excel in real-world applications.

Aligned with the established objectives, this thesis presents a series of contributions. Firstly, it introduces a Linux Kernel implementation of the MEADcast router, facilitating the deployment of MEADcast in a real network. Second, it offers a traffic generator designed to serve as the MEADcast sender, simulating the application of the protocol. These contributions are further solidified through the deployment of MEADcast in both a controlled testbed environment and a real-world network. Lastly, this research evaluates MEADcast's feasibility, performance, and potential application scenarios based on a series of conducted experiments. This evaluation provides valuable insights for its future implementation and development, ultimately enabling us to propose a revision of the protocol specification.

The findings indicate, that with certain limitations, MEADcast is applicable in real networks. The current protocol specification suffers from poor availability on the internet due to the limited processing of IPv6 packets with extension headers. However, the proposed modification effectively addresses this obstacle while enhancing receiver privacy. Our measurements suggest that MEADcast's performance falls between uni- and multicast, particularly showing promise in scenarios characterized by limited bandwidth and network control.

1.4 Method

To ensure the achievement of the previously defined goals, this thesis follows the procedure illustrated in Figure 1.1. First, we conduct a literature review of several multicast protocols and analyze the current challenges of global multipoint communication. With a clear understanding of the relevant protocols and their limitations we define the objectives of this thesis. Furthermore, we select adequate evaluation metrics and criteria to asses MEADcast's feasibility, performance, and potential application scenarios. Subsequently, we design a series of experiments aimed at capturing these metrics. Next, we outline the testbed requirements

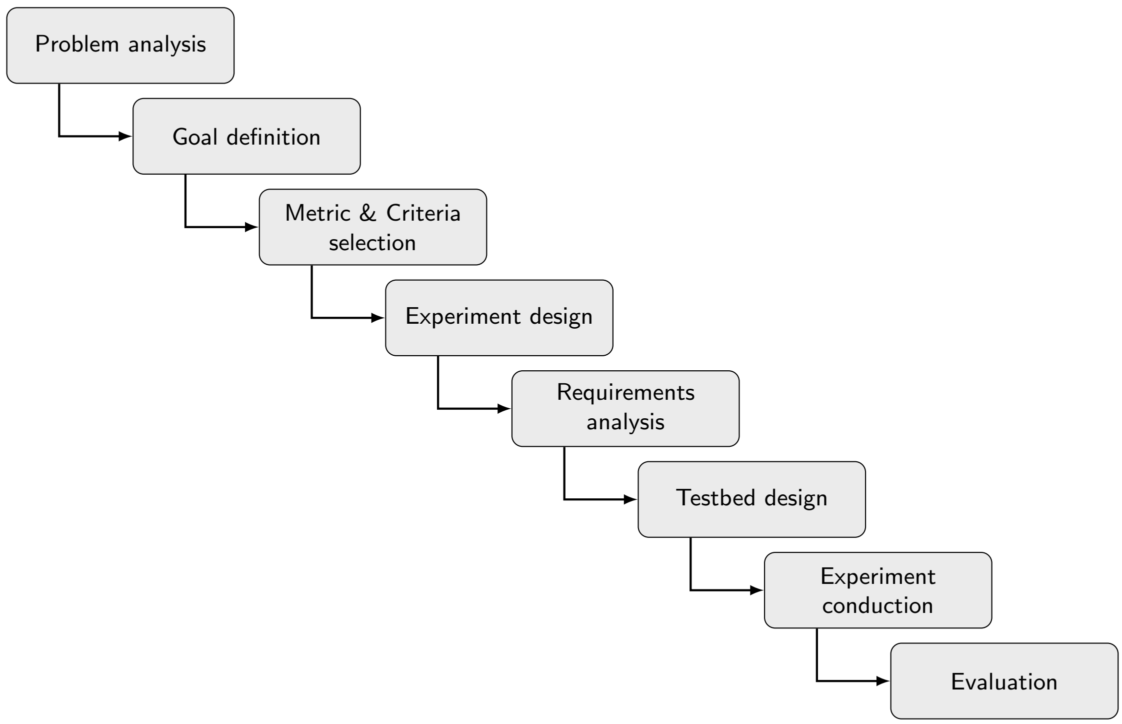

Figure 1.1: Research method

derived from these experiments and elaborate on a corresponding testbed design. MEADcast is then deployed in the testbed, and the experiments are conducted. Finally, we present the obtained results. These findings are critically evaluated with respect to the thesis' overarching goal, providing valuable insights into the feasibility and performance of MEADcast. This analysis allows us to identify scenarios and applications for which the protocol is well-suited.

1.5 Structure

The method employed in this thesis ensures a cohesive narrative, with each chapter building upon the knowledge acquired in the previous sections. Chapter 1 depicts the motivation for investigating multipoint communication, highlights the current challenges of IP-Multicast, and articulates the goal of this thesis. Moving forward, Chapter 2 establishes the theoretical foundation for subsequent investigations, by examining several multicast protocols, including IP-Multicast, Xcast, and MEADcast. Additionally, the chapter provides a brief overview of Kernel development fundamentals and the network stack, laying the groundwork for the router implementation. Chapter 3 presents our selection of evaluation metrics and criteria, outlines the testbed requirements and presents the corresponding testbed design. Chapter 4 delves into technical details about the Kernel implementation of the router software and provides detailed specifications of the testbed. This chapter serves as the foundation for the practical experiments. In Chapter 5 we present the results from our experiments and evaluate them. Finally, Chapter 6 summarizes the findings and draws conclusions from this research. Additionally, it outlines potential avenues for future work and exploration in this field.

2 Background and Related Work

2.1 Multicast Protocols

Multicast communication refers to the simultaneous delivery of data towards an arbitrary number of destinations [KPP93; LN93]. Numerous network protocols have been developed to facilitate multicast communication, encompassing both Network Layer as well as Application Layer implementations [Zha+06; ST02]. This chapter first distinguishes Multicast from other communication schemes. Subsequently, various multicast protocols are introduced.

According to the OSI model [Zim80] Layer 3, known as the Network Layer, is responsible for end-to-end delivery of data between nodes. In computer networks data is transferred through Protocol Data Units (PDUs), composed of protocol specific control information (e.g. source and destination address), along with a payload carrying the actual data. To establish a path from the sender to the destination(s), packets (Layer 3 PDUs) may traverse multiple intermediate nodes [Pos81]. This process is called routing and can be classified into various schemes. For the purpose of this thesis, our primary focus lies on the schemes depicted in Figure 2.1. *Unicast* denotes a one-to-one association between a sender and a single destination. *Broadcast* disseminates packets to all nodes within the sender's broadcast domain (Layer 2) [Mog84]. Typically, IP Routers (Layer 3) serve as the boundary of a broadcast domain. *Multicast* transmits packets to a group of destinations, accommodating both one-to-many and many-to-many communication [Dee89]. In contrast to Broadcast, Multicast does not necessarily deliver packets to all available nodes. Furthermore, Multicast packets can be delivered beyond the sender's broadcast domain, implying subsequent replication of the packets.

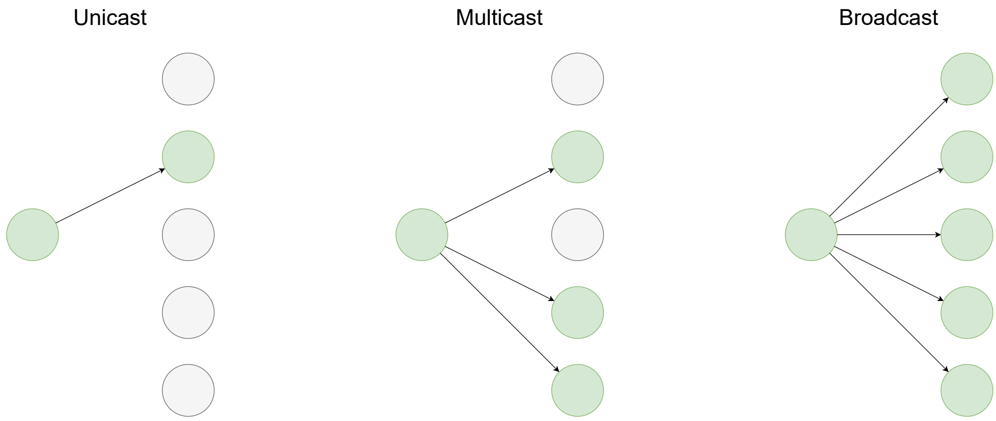

Figure 2.1: Network Layer: Routing schemes

2.1.1 IP Multicast

- Separate address space
- IGMP / MLD
- Intra-Domain Routing: DVMRP, MOSPF, PIM dense/spare
- Inter-Domain Routing: MBGP, MSDP

2.1.2 Xcast

Traditional multicast scales well with large multicast groups but have issues with a high number of distinct groups. Xcast is a mutlicast protocol with complementary scaling properties compared to the traditional approach [Boi+07]. The protocol is designed with the key idea of supporting huge numbers of small multicast sessions. Xcast achieves this by explicitly encoding the receiver addresses in each packet, instead of using a multicast addresses [Boi+07].

2.1.3 MEADcast

2.2 Linux Kernel

2.2.1 Fundamentals

2.2.2 Network Stack

3 Experiment Design

This chapter addresses the design of a series of experiments to evaluate MEADcast. To ensure the quality of the experiments Section 3.1 discusses research questions driving our design process. Subsequently, Section 3.2 elaborates on motivations for employing multicast, potential application domains and their characteristics. This chapter deals with the selection of measurements, design of experiments and the design of a testbed based on requirements derived from the experiments.

Based on thesis goal we first formulate overarching research questions we endeavour to answer with our experiments. Therefore, these questions guide our design process of the experiments.

3.1 Measurements

Aligned with the goal of this thesis, we begin by formulating overarching research questions, guiding the design of the experiments. Additionally, this section outlines our approach to answering these questions.

RQ1 How robust is the current MEADcast specification?

While prior research on MEADcast has primarily taken place in simulated environments [TD18; DT19] and small stub networks [Ngu19], this thesis endeavors to assess MEADcast in a more realistic setting. To achieve this, we perform a stress test to evaluate the protocol's behavior in a less "clinical" environment. During this test we observe MEADcast's reaction to deliberate routing changes, to evaluate its adaptivity and suitability for dynamic network environments. Further, we simulate network disruptions by inducing router outages, to assess MEADcast's resilience and recovery capabilities. The stress test also examines MEADcast anomaly handling by injecting modified discovery responses. Additionally, a firewall is employed to intentionally drop MEADcast packets during the data delivery phase, enabling us to evaluate the efficacy of the fallback mechanism. The results of the stress test shed light on the robustness of the current MEADcast specification, especially in diverse network conditions. This investigation aims to provide valuable insights into the real-world applicability and resilience of MEADcast.

RQ2 How does MEADcast perform compared to IP-Unicast and IP-Multicast?

In addition to assessing the robustness of a protocol, its performance, especially in comparison to existing alternatives, is a pivotal factor influencing its adoption. To address this research question, comparative performance measurements for MEADcast, IP-Unicast, and IP-Multicast are conducted across a series of experiments elaborated in Section 3.2. These measurements encompass metrics such as throughput, latency, jitter, and resource utilization. Special attention is given to the impact of MEADcast's discovery phase on its performance. This encompasses assessing the overhead produced by the discovery mechanism. Furthermore, we evaluate how the protocol's shift from extensive unicast to MEADcast delivery affects the performance metrics. The outcomes contribute not only to evaluating MEADcast performance but also to drawing conclusions for subsequent research questions.

RQ3 *Which applications and characteristics are well served by MEADcast?*

Addressing this research question involves designing a series of experiments depicting a diverse range of applications with distinct characteristics (see Section 3.2). The selection of scenarios is guided by an initial exploration of motivations for employing multicast communication, and more specifically, MEADcast. These motivations lay the groundwork for identifying a range of potential application domains where MEADcast deployment could prove beneficial. Subsequently, we formulate application characteristics distinguishing these domains. Based on the gathered insights, various scenarios are chosen to represent different application domains and their unique set of characteristics. This comprehensive selection ensures a throughout examination of MEADcast's suitability across a diverse spectrum of use cases. The results aim to delineate MEADcast's application space by identifying its strengths and limitations.

RQ4 *In which conditions is the usage of MEADcast sensible?*

The viability of employing MEADcast is influenced not only by application domains and their characteristics but also by prevailing circumstances. To investigate this aspect, the experiments are executed with various parameter configurations. For instance, the level of network control and the number of available MEADcast routers affect the performance and thus the viability of MEADcast. This applies equally to testing parameters like available bandwidth, number of endpoints, and their distribution. The goal is to provide insights into the conditions under which deploying MEADcast is advantageous compared to existing alternatives. The results aim to offer guidance for making informed decisions regarding the adoption of MEADcast in specific circumstances.

3.2 Scenarios

To design comparable experiments we have to elaborate on application domains that may benefit from Multicast-Communication. Following, we formulate application characteristics distinguishing these domains. This knowledge enables us to design a series of experiments representing a variety of application domains with differing characteristics. Thereby we aim to answer RQX.

3.2.1 Motivations for employing Multicast

To select appropriate measurements and experiments, it is essential to delve into the *motivations* for employing multicast communication and, specifically, MEADcast as a protocol.

In a broader context, the decision to utilize multicast often resolves around optimizing resource usage. In the absence of resource constraints, one might question opting for multicast rather than ubiquitous unicast communication. However, several compelling reasons advocate for the adoption of a multicast protocol. A predominant motive is overcoming *resource limitations*, which can manifest technically, such as a network connection incapable of providing the required bandwidth, or Internet of Things (IoT) devices like IP cameras struggling to handle numerous unicast connections requesting identical content.

Financial considerations are also a driving reason for employing multicast, since most internet services operate on a subscription or pay-as-you-go pricing model (pay per usage). ISPs, mobile phone operators, and VPN providers structure their services based on factors like monthly available traffic volume, upstream and downstream bandwidth. Subscribed service levels can thus become the financial cause of resource limitations. Cloud providers, in particular, heavily rely on pay-as-you-go pricing, often contending their customers with expensive "egress costs". Deploying multicast emerges as a strategic approach to not only overcome technical and financial constraints but also to reduce operational costs.

Another motivation for multicast adoption is to facilitate new services or enhance existing ones. For example, employing multicast for delivering multimedia content enables service providers to offer higher-quality audio or video without the need to either increase operational costs or overcome prevailing resource limitations. Moreover, multicast can empower individuals to access bandwidth-intensive services despite their limited bandwidth. For instance, peer-to-peer (P2P) conferencing services could leverage multicast to bridge the asymmetric access link common in most households (high downstream and low upstream bandwidth) [Boi+07]. Additionally, network operators may strategically deploy multicast within their domain to decrease overall network load, concurrently reducing operational costs and mitigating emissions caused by CT (see Section 1.1).

As constituted in Section 1.2 and Subsection 2.1.1, in many scenarios, the usage of IP-Multicast is not a viable option. This creates a potential application space for MEADcast, particularly in circumstances with limited network control and an uncertain degree of IP-Multicast support. Another potential domain for MEADcast is in facilitating access control-based multicast communication, addressing the absence of a receiver authorization mechanism in IP-Multicast [Dio+00]. In comparison to alternatives like Xcast or Application-Layer Multicast (ALM), MEADcast might be favored in situations where the disclosure of receiver information, such as IP addresses, among other group members, is deemed unacceptable.

3.2.2 Application Domains

As highlighted in the preceding section, numerous motivations support the adoption of multicast communication. Additionally, various types of applications have the potential to benefit from multicast communication. However, it is essential to acknowledge that multicast is tailored for a specific form of communication – *simultaneous* transmission of *identical* data to multiple recipients, as delineated in Table 3.1. This inherent characteristic finds an ideal match in TV broadcasts, establishing them as a prime candidate for multicast communication. Conversely, Video on Demand services such as YouTube present a less favorable scenario for multicast adoption, as users request videos at different points in time. The advantages of multicast become particularly evident in bandwidth-intense applications, where its potential to significantly reduce the total communication volume is most pronounced. Real-time multimedia services, therefore, emerge as a particularly well-suited domain for the application of multicast. In the following, we present our formulated application domains supported by exemplary applications. The characteristics distinguishing these domains are discussed in the following section.

The first application domain is *Multimedia Streaming*, encompassing various applications transmitting multimedia content to an arbitrary number of destinations, such as IPTV

	Temporal	
Content	Synchronous	Asynchronous
Identical	TV broadcast (yes)	Video on demand (no)
Different	- (no)	Web browsing (no)

Table 3.1: Suitability of communication patterns for Multicast

[DT19; RES06], Internet Radio [TD18], podcasts, and live streaming (e.g. Twitch). *Conferencing and Collaboration* is the second domain, comprising Audio and Video Conferences [ST02; DT19; KPP93], Voice over IP (VoIP) [BGC04; Boi+07], as well as real-time collaboration applications [Dio+00; Boi+07] like online Mind Maps and Whiteboards. The next domain *File Transfer*, covers numerous applications distributing files to multiple recipients, including Software Distribution and Updates, Patch Management [TD18; RES06], Logging [Dio+00] as well as file sharing and synchronization [ST02]. *Information delivery* comprises applications pushing information to multiple destinations. One example is a news application, which notifies it's users about new information of topics or channels they have subscribed [Dio+00]. Other applications include widely utilized smartphone notifications, RSS feeds [RES06], Logging (e.g. SNMP), and Stock quotes [Cis01]. The last domain is *Distributed Simulation*, with exemplary applications such physics simulations [Dio+00], virtual reality, and online gaming [RES06].

Domain	**Applications**
Multimedia streaming	IPTV, Internet Radio, podcasts, streaming platforms
Conferencing & Collaboration	Audio- & Video-Conferences, VoIP, Mindmaps, Whiteboards, ...
File Transfer	Software Distribution, Updates, Patch Management, File-sharing and -synchronization, Logging
Information delivery	Push notifications, RSS-feed, Logging, Stock quotes
Distributed simulation	Online Gaming, Virtual World, Simulation

Table 3.2: Multicast application domains

3.2.3 Application Characteristics

This section delineates various characteristics derived from the application domains, categorized into three groups:

Group Group communication occurs in diverse forms. The number of participants in a multicast group displays substantial variation, ranging from small (< 10), to medium-sized and up to large-sized (> 100) groups. Additionally, the session duration exhibits significant

Scenario	Group/Session			Communication		Network		
	Duration[1]	Membership	Size	Pattern	Interval	Pkt. size	Through. (tx/rx)	Latency /Jitter
Livestream	h-d	dyn.	l	1:n	steady	med.	high/med.	med.
Conference	m-h	stat.	s-m	m:n	steady	med.	high/high	low
File transfer	s-h	stat.	s-l	1:n	burst	large	high/high	high
Push info.	s	stat.	m-l	1:n	burst	small	med./low	med.
Online game	m-h	stat.	s-m	m:n	steady	small	low/med.	low

[1] *(s)econds, (h)ours, (d)ays*

Table 3.3: App Scenarios

diversity, spanning from a few minutes up to several days. The group *membership* can either be static or dynamic. For instance, small to medium-sized conferences might last several minutes to a few hours with mostly static group membership. In contrast, broadcasts of music or sports events endure for several days, attracting millions of viewers who may join or leave at any time.

Communication The communication *pattern* within a group can either be symmetric (m:n) or asymmetric (1:n). Furthermore, the *interval* during which participants exchange messages may constitute a steady flow (e.g. video stream) or a recurring burst (e.g. file transfer). In a P2P video conference or online game, all group members continuously transmit data to each other. Conversely, in an RSS feed, a single server periodically pushes information to multiple subscribers.

Network The network requirements of different applications exhibit significant variation. Specific applications exhibit sensitivity to distinct factors, with some prioritizing low *latency* and *jitter*, others demanding high *throughput*, and yet others being sensitive to the packet *drop rate*. For instance, many online games rely on low latency while maintaining frugal bandwidth requirements [Har+07]. In contrast, ensuring a high-quality video stream necessitates elevated throughput, even though increased latency is acceptable due to prevalent client-side buffering. Furthermore, an RSS feed has low throughput and moderate latency requirements. Nevertheless, it is sensitive to the packet drop rate, since it has to ensure successful data delivery.

3.2.4 Application Scenarios

3.3 Testbed

3.3.1 Requirements

3.3.2 Architecture

	Communication		Network			Group/Session		
Scenario	Pattern	Interval	Pkt. size	Through. (tx/rx)	Latency /Jitter	Duration[1]	Mem. ship	Size
Live Stream	1:n	steady	med.	high/med.	med.	h-d	dyn.	l
File transfer	1:n	burst	large	high/high	high	s-h	stat.	s-l
Conference	m:n	steady	med.	high/high	low	m-h	stat.	s-m
Online Game	m:n	steady	small	low/med.	low	m-h	stat.	s-m

[1] *(s)econds, (h)ours, (d)ays*

Table 3.4: Show diff scenarios meeting

Based on the goal, formulated in Section 1.3 we derived the following questions:

- How does MEADcast perform compared to unicast and multicast?
- Under which conditions is the usage of MEADcast sensible?
- Which applications and characteristics are well served by MEADcast?
- How robust is the current MEADcast specification?
- Is MEADcast usable in "real" networks?
- Are there any issues or opportunities for improvement with the current protocol specification?

Robustness

- How does MEADcast handle routing changes?
- How does MEADcast handle router failure?
- How does MEADcast handle malicious packets? *(e.g. invalid discovery response)*
- Does the fallback mechanism work properly? *(e.g. turn on a firewall)*
- How does the sender/router handle high MEADcast load?

Discovery Phase

- Impact/Overhead of the discovery phase?
  - Is there a drop in total transferred bytes/packets after the initial discovery phase?
  - How does the recurring discovery phase influence the measured performance metrics?
- Sensible discovery interval?

Characteristics (testing parameters)

- Endpoint distribution *(avg. distance & EPs per route)*
- Group size *(small vs. big)*
- Session duration *(short vs. long)*
- Membership *(static vs. dynamic)*
- Available bandwidth *(low vs. high)*
- Latency or bandwidth sensitivity *(many small packets vs. few big ones)*

Availability

- Is MEADcast usable with intermediate notes like firewalls & routers? *(Does it work at all? Does the fallback mechanism work?)*
- Is MEADcast usable on the internet?

KPIs

- Total transferred bytes/packets
- Latency & Jitter
- Packet loss
- Resource utilization *(CPU, Memory, Link)*
- Hop count & header size *(mainly for internet availability)*

Scenarios

- Simulate typical application
  - Video conference *(may server vs. P2P)*
  - Live stream
- Test these in different topologies with varying parameterization *(see Characteristics)*

4 Implementation

```
 0                   1                   2                   3
 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|  Next Header  |  Hdr Ext Len  |  Routing Type |    Num. Dst   |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|Fl.|    Hops   |                    Reserved                   |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|                          Delivery Map                         |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|                           Router Map                          |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|                                                               |
.                                                               .
.                          Address List                         .
.                                                               .
|                                                               |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
```

Figure 4.1: Python: MEADcast Header

```
 0                   1                   2                   3
 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|  Next Header  |  Hdr Ext Len  |  Routing Type | Segments Left |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|    Num. Dst   |Fl.|    Hops   |            Reserved           |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|                          Delivery Map                         |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|                           Router Map                          |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|                                                               |
.                                                               .
.                          Address List                         .
.                                                               .
|                                                               |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
```

Figure 4.2: Current: MEADcast Header

Routing Type	Since there is no existing Routing Type for MEADcast we use the experimental values of 253 and 254 according to RFC3692 [Nar04].
Segments Left	Fixed to zero and is not altered by MEADcast routers. Thereby intermediate nodes, which does not recognize the used Routing type value must ignore the MEADcast header and process the next header [DH17].
Num. Dst.	Indicates the length of the address list.
Flags	1 bit discovery, 1 bit response
Hops	This field is used during the discovery phase. The sender initializes the field with zero and gets incremented by each MEADcast router.
Delivery Map	Bitmap indicating, whether an address in the address list needs to be delivered.
Router Map	Bitmap indicating, whether an address in the address list is a router.
Address List	Variable length list of IPv6 addresses.

Table 4.1: MEADcast Header field description

4.1 Router

4.2 Testbed

5 Evaluation

6 Summary

6.1 Conclusion

6.2 Further Work

List of Figures

Acronyms

ALM Application-Layer Multicast. 9

CT Communication Technology. 1, 9

IoT Internet of Things. 9

ISP Internet Service Provider. 2, 9

P2P peer-to-peer. 9, 11

PDU Protocol Data Unit. 5

SDN Software-defined networking. 3

VoIP Voice over IP. 10

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