# INSTITUT FÜR INFORMATIK

## DER LUDWIG–MAXIMILIANS–UNIVERSITÄT MÜNCHEN

**Masterarbeit**

# MEADcast Evaluation & Linux Kernel Implementation of the Router

Adrian Schmidt

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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

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*(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*. 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 ISPs have shown limited efforts to deploy Multicast within their Administrative Domains [Dio+00; RES06]. 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. 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

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[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.

Based on the defined objectives, this thesis makes the following contributions:

1. Development of a Linux Kernel implementation of the MEADcast router.

2. Implementation of a traffic generator serving as the MEADcast sender.

3. Deployment of MEADcast in both a testbed and a real network.

4. Evaluation of MEADcast's feasibility, performance, and potential application scenarios, derived from the conducted experiments.

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
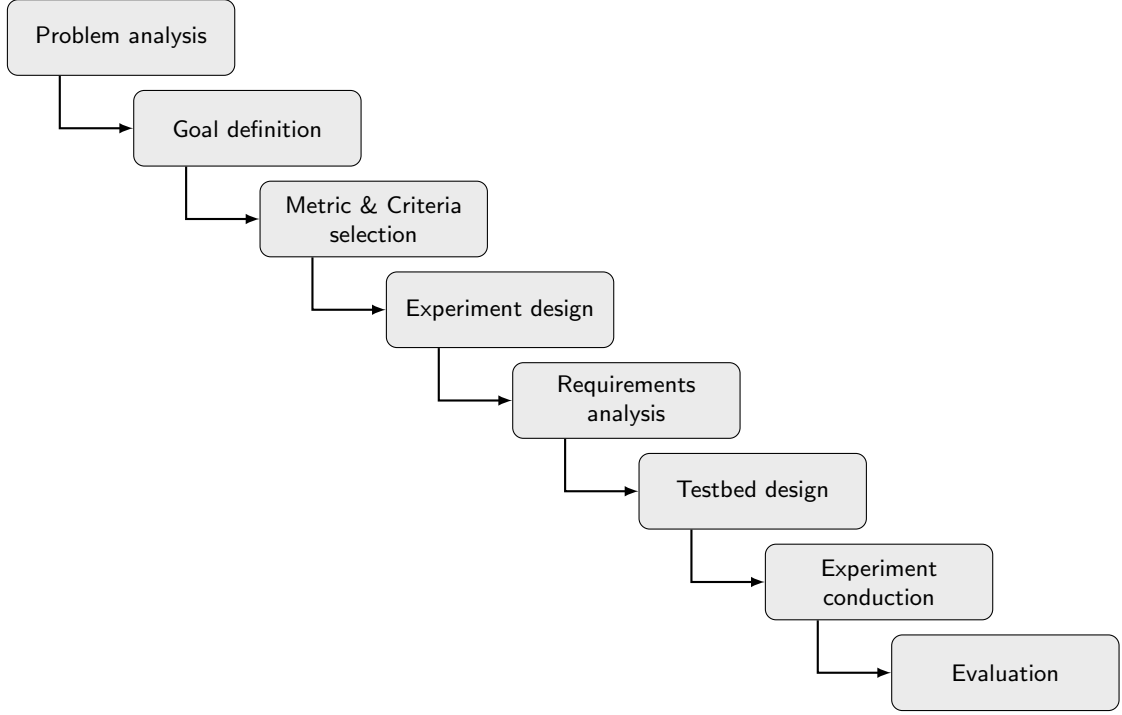
Figure 1.1: Research method

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 is a technique of sending data one-to-many or many-to-many. Related technologies are unicast, broadcast and anycast.

### 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 Design

## 3.1 Metrics

## 3.2 Experiments

## 3.3 Testbed

### 3.3.1 Requirements

### 3.3.2 Architecture

# 4 Implementation

## 4.1 Router

## 4.2 Testbed

# 5 Evaluation

# 6 Summary

## 6.1 Conclusion

## 6.2 Further Work

# List of Figures

# Acronyms

**CT** Communication Technology. 1

**SDN** Software-defined networking. 3

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