INVESTIGATION OF PUSH-BASED TRAFFIC FOR CONVERSATIONAL SERVICES IN NAMED DATA NETWORKING

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ABSTRACT

Conversational services (e.g., Internet telephony) exhibit hard Quality of Service (QoS) requirements, such as low delay and jitter. Current IP-based solutions for conversational services use push-based data transfer only, since pull-based communication as envisaged in Named Data Networking (NDN) suffers from the two-way delay. Unfortunately, IP's addressing scheme requires additional services for contacting communication partners. NDN provides an inherent solution for this issue by using a location-independent naming scheme. Nevertheless, it currently does not provide a mechanism for push-based data transfer. In this paper, we investigate Persistent Interests as a solution for push-based communication. We improve and implement the idea of Persistent Interests, and study their applicability for conversational services in NDN. This is done by comparing different push- and pull-based approaches for Internet telephony.

***Index Terms*—** Information-Centric Networking; Named Data Networking; Conversational services; Push-based traffic

1. INTRODUCTION

During the last decade the importance of Internet telephony increased steadily. One of the ideas of Internet telephony was to introduce a location independent service in IP-based networks. Due to the location dependent nature of IP's addressing scheme, it is challenging to manage Internet telephony in today's networks. In order to achieve location independence, the state of the art – Voice over IP (VoIP) – uses the Session Initiation Protocol (SIP) [1] to establish and manage calls. One challenge for SIP is that the IP address of communication partners can not be easily determined. Therefore, SIP introduces additional components like Redirect, Proxy and Registrar Servers. The necessity of these additional services indicates that IP-based networks are not well suited for Internet telephony due to their location dependency.

Information-Centric Networking (ICN) [2] is a novel Internet architecture that provides an inherent solution to the aforementioned challenges. This is due to the fact that there is no location-dependent addressing scheme in ICN. Instead of addressing hosts, the data itself is named. Every content has its system-wide unique, location-independent name. In terms of Internet telephony, there is no need to know a host address any more. By smart usage of the naming scheme, a communication partner can be contacted directly via his/her name at the initiation of a call. The requested name is used to find the communication partner in the network, regardless of his/her current geographic position. This means that ICN enables the direct addressability of communication partners without the need of additional Proxy or Registrar Servers.

In this paper, the understanding of ICN is coincident with Named Data Networking (NDN) [3]. In NDN a client requests Data by sending an Interest packet containing the name of the requested data to the network. The Interest is forwarded to neighbouring nodes based on decisions made in the forwarding plane. Once the Interest reaches a node maintaining a replica of the requested data, a Data packet carrying the data is sent back to the requesting client. The Data packet strictly flows back on the reverse path of the Interest, using information stored in the so-called Pending Interest Table (PIT).

The objective of this paper is to investigate the feasibility of Internet telephony in Named Data Networking using push- and pull-based approaches for transmitting voice data. To enable push-based communication in the usually pull-based NDN environment, we improve and implement the idea of Persistent Interests (PI) [4]. Further, we compare the push-based approach with existing pull-based ones. Then, we investigate the influence the PIs' refresh interval and of network-level queuing on voice streams. We also provide an open-source implementation of PIs that can be used for further research in NDN.

2. RELATED WORK

Jacobson et al. [5] performed pioneering work in the field of voice over ICN. They analyzed the currently used SIP protocol and transformed it into VoCCN, a SIP-compatible Internet telephony protocol for ICN. Conversational voice traffic is delay sensitive. A maximum delay of 100 ms between the generation and the delivery of a voice packet should not be ex-

978-1-5386-0560-8/17/$31.00 ©2017 IEEE

ceeded, as the International Telecommunication Union (ITU) points out [6]. For this reason, Jacobson exploits the hierarchical naming scheme of NDN to request data which is not yet produced. The main idea is to send an Interest for a future voice packet to the communication partner. The communication partner keeps the Interest pending until the corresponding Data is produced. When the corresponding voice packet is generated, it is immediately sent back to the requester. By using this technique, the delay between the generation of a voice packet and the delivery can be reduced from the round-trip time to the one-way delay as in push-based approaches. We use this improvement for comparisons and refer it to as *pre-requesting data* approach in later sections.

As discussed in previous work [7], sending an Interest for each Data packet can lead to inefficiencies with respect to overhead and response time. Therefore the concept of Persistent Interests (PI) or Long Term Interests [7, 4] was introduced. The idea behind PIs is that multiple data packets are requested with a single Interest. This reduces the network overhead and relieves the network core, because fewer Interests must be processed. A classical Interest is sent over the network and stored in the Pending Interest Tables (PIT) [3] of all forwarding nodes. If a matching Data packet is received, the corresponding PIT entry is marked as satisfied and deleted from the PIT. PIs behave similarly, the only difference is that a PIT entry of a PI is not marked as satisfied if a matching Data packet passes the node, but it stays in the PIT until its predefined lifetime times out. A first performance evaluation [4] showed that the number of sent Interests and the PIT size is appreciably reduced by the use of PIs.

Posch et al. [8] showed that the performance of conversational services could also be enhanced by changes in the forwarding plane. They integrated context information, e.g. QoS demands, in the forwarding decision and analyzed the improvement on service quality by conducting network simulations. Now that we know that context-aware forwarding improves QoS, we want to find more factors for improving the service quality of conversational services in NDN. Research has shown [9] that the service quality in IP networks can be improved by using different queuing strategies on network level. Nevertheless, the influence of network-level queuing on QoS in NDN has not been investigated and will be in the focus of this paper.

3. PERSISTENT INTERESTS

Data transfer in NDN follows a strict pull-based nature. Every single Data packet is first requested by an Interest. Each Interest is requesting only a single Data packet. Unfortunately this strict pull-based nature leads to challenges in some use cases. Conversational services like Internet telephony or video conferences are examples.

One challenge of a conversational service is that the characteristics of the data to transport is not known before the transmission. For example, a video requires a high bitrate if there is a lot of movement in the video and a low bitrate if there is only little movement. There are two possibilities to request variable-bitrate videos in NDN, where every packet has to be requested by an Interest: i) Agree on a fixed number of packets per second and send out the same amount of Interests each second. This could lead to a transmission of nearly empty packets at low-bitrate video sequences or large packets at high-bitrate video sequences. Nearly empty packets lead to inefficiencies due to overhead, too big packets could lead to problems regarding the maximum transmission unit. ii) Vary the number of constant-size packets. In this case the client has to know how many packets have to be requested each second, which is difficult at conversational services because the required video bitrate is not known before.

Another challenging factor for conversational services are the delay requirements. For Internet telephony, as well as in video conferences, the delay should be as low as possible. The two-way delay resulting from requesting each packet by an Interest can be reduced by pre-requesting future packets. Nevertheless, it gets difficult to pre-request packets at sources with different packet generation rates.

Pushing Data from the source to the client offers one solution for both problems. If Data is pushed, the resulting delay is the one-way delay and there is no need for the client to know how many packets per second are produced. Persistent Interests (PI) enable push-based data transfer in NDN. A PI is an Interest which does not request a single Data packet, but all Data packets which are produced within a predefined time interval. According to Tsilopoulos et al. [7] PIs should be used for conversational services, because they reduce inefficiencies and lead to a higher QoE. In the next section we give details on PIs and their implementation.

3.1. Implementing Persistent Interests

When implementing PIs, we focus on changing as little as possible of the NDN concept. Therefore, the naming scheme stays the same. For instance, if a voice call to *Alice* is established, the Name requested by a classical Interest could be `/alice/voip/[seq]`, where `[seq]` refers to an increasing sequence number addressing a packet of the voice stream. In the case of PIs, we omit this number and request `/alice/voip`. The names of the Data chunks stay the same. The reply to the PI are Data packets of the voice stream: `/alice/voip/[seq]`, `/alice/voip/[seq+1]`, ...

The NDN nodes are responsible for forwarding Interests and delivering Data packets. It is important that an NDN node can differentiate between a classical Interest and a PI, because a PI must not be deleted after receiving a Data packet. To facilitate this distinction we include a `type`-field in Interest packets, similar as described by Yao et al. [4]. To reduce overhead, this field is only encoded and sent if the value differs from the default value for classical Interests. This means that there is no additional overhead for classical Interests. The structure of Data packets stays unchanged because there is no difference in processing a Data packet when it is requested by a PI.

The Pending Interest Table (PIT) is a core data structure of an NDN node and has to be adapted for PIs. Instead of removing a so called PI-PIT entry when a Data packet arrives, the entry has to be kept pending until its predefined lifetime times out. If another PI for the same name arrives, the lifetime of the PI is reset. This feature is used to refresh PIs before they time out. PIs sent for refreshing the lifetime are referred to as refresh PIs.

3.2. The Interplay of Forwarding Strategies and PIs

When an Interest arrives at an NDN node, the node has to decide where to send the Interest packet next; this is referred to as the forwarding decision. The forwarding decision is made by a forwarding strategy in the NDN node. A forwarding strategy makes use of two other components; i) the Forwarding Information Base (FIB), which contains information about which name is available with what costs on which face, and ii) the PIT. It is possible to make forwarding decisions based on information from these two components, but it is hard to react to sudden changes of the network, such as congested links or link failures. More sophisticated forwarding strategies calculate and use additional information based on packet statistics. Two examples are the Best-Route forwarding strategy [10], which checks if retransmissions occur and utilizes other faces for retransmitted packets, and Stochastic Adaptive Forwarding [11], which checks the Interest satisfaction ratio on outgoing faces and shifts parts of the traffic to other faces if the ratio is too low.

When using PIs, the calculation of such parameters is not easily possible. The traffic pushed as a result of a PI is not retransmitted by default. This makes it impossible to react on retransmissions, as the Best-Route forwarding strategy does. Also the second mentioned parameter, the interest satisfaction ratio can not be calculated when using a PI. The interest satisfaction ratio is the ratio between all transmitted Interests on a face and the satisfied Interests[1] on the same face. The nature of a PI is that multiple Data packets belong to one PI, which makes the calculation of the Interest satisfaction ratio hard. This observation shows that common forwarding strategies are not applicable for push-based traffic without modifications.

For a first investigation, we want that PIs are forwarded to the best available face, which is the behaviour of the Best-Route forwarding strategy. Therefore, we extend the Best-Route forwarding strategy for PIs. Without being aware of PIs, Best-Route would identify refresh PIs as requests for retransmissions and would drop them. Our extension disables the retransmission detection for PIs by using the `type`-field of Interest packets. So the extended Best-Route forwarding strategy can be used for both, classical Interests and PIs.

[1] An Interest is referred to as satisfied Interest if the corresponding Data packet was received.

4. EVALUATION

In this section we investigate the performance of push-based data transfer using the Persistent Interest (PI) approach by comparing it to the classical NDN approach and the improvement proposed by Jacobson et al. [5]. In addition we use different queuing strategies for network-level packet queuing in order to observe the influence of queuing on service quality in NDN. The comparison is done by conducting network simulations using the network simulator ns-3/ndnSIM [10].

4.1. Scenario Description

The idea of our scenario is to simulate Internet telephony calls in a large computer network. For this purpose, we generate a network containing five interconnected autonomous systems. During ten simulated minutes, 20 phone calls are simulated. The participants of the calls are randomly placed clients. Through this setting, we get both, inter- and intra-autonomous system calls. In order to see differences of the used approaches, we congest links by adding cross-traffic.

The network topology for the scenario is randomly generated using the network topology generator BRITE [12]. BRITE was configured to generate five interconnected autonomous systems. Each of the autonomous systems consists of 20 nodes, which are acting as NDN routers. In order to show the limitations and benefits of each variant, we configured link speeds in a way that forces congestions on some links. The links connecting two nodes in one autonomous system utilize between 500 and 1500 kbps, uniformly distributed. The bandwidth of the links interconnecting two autonomous systems lies uniformly distributed between 3000 and 5000 kbps. Figure 1 shows a sample topology of the network core without clients, used during the network simulations.

For simulating the phone calls, we used the fixed bitrate G.711 codec [13]. A voice stream encoded with this codec produces 64 kbps of raw voice data, uniformly distributed in 100 packets per second, each carrying 80 bytes of payload. The average call length is 2.5 minutes, which is the average duration of cell-phone calls according to the German Bundesnetzargentur [14].

As cross-traffic, we use four randomly placed NDN producer/consumer pairs. Each client requests 100 packets per second. Requested Data packets carry 1 kB of payload. During all settings, cross-traffic always uses the classical NDN approach to transport data.

For measuring the performance of the different approaches, the quality of the voice traffic is of major importance. To measure the quality of a voice call the ITU recom-

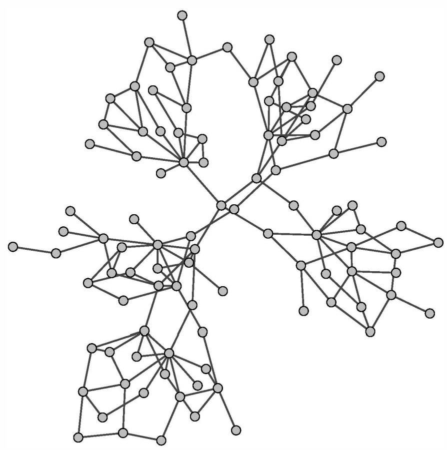

Fig. 1. Example core topology for network simulations

mends the E-Model [13]. It takes all possible impairments, like equipment-based impairments or delay-related impairments, into consideration. Equipment-based impairments are only of minor importance for our investigations. Therefore, we use the simplified E-model [15], which is an extension of the E-Model and should be used for network-level studies. It utilizes constants for impairments by speech quantization and codec-dependent factors like delay impairments and the packet loss concealment ability. Furthermore, this model allows the estimation of the Mean Opinion Score (MOS) of Internet telephony based on packet statistics, which is an important and well known Quality of Experience (QoE) metric. Beside the estimated MOS value, we use the delay between the generation and delivery of a voice packet and the number of sent packets/kilobytes as additional performance metrics.

The compared approaches are i) using Persistent Interests (PIs), ii) pre-requesting data packets as in [5], and iii) the classical NDN approach. PIs are implemented as described in Section 3. The lifetime of a PI is set to five seconds. In order to prevent timeouts, a PI is refreshed every two seconds, which means that a voice stream would not be interrupted if a refresh PI is lost. For pre-requesting future voice packets, we reuse the voice client from [8] and request voice packets 250 milliseconds before their creation. The classical NDN approach requests Data packets in the moment of their generation.

For analyzing the influence of different network-level packet queueing strategies on service quality, multiple queues were implemented and used. The standard FIFO-Queue with Taildrop as drop policy and the Random Early Detection (RED) strategy were already implemented in ns-3/ndnSIM. In addition to these queuing strategies, Priority Queuing, Fair Queuing and Weighted Fair Queuing (WFQ) were implemented and published on GitHub[2]. The size limitations were implemented on packet and on byte level. Since WFQ is not designed for packet-wise scheduling, only byte-wise size limitations were investigated for this strategy. The queue size in the simulation is set to 50 packets; for byte-level size boundaries, we assumed an average packet size of 1 kB, which leads to a queue size of 50 kB. Priority Queueing as well as WFQ use context information like QoS demands of a packet to control the service quality. To classify packets into different service levels, QoS Class Identifiers (QCI) [16], originally proposed for LTE networks, are implemented and used. QCI class 1 (Conversational Voice) is applied for all Internet telephony packets, including Interests and Data. Untagged packets, including cross-traffic, are handled with the default QCI class 9. For the separation of traffic flows used by Fair Queuing and Weighted Fair Queuing, the first two parts of the NDN naming scheme are used. Therefore the names of the voice packets are in the form `/voip/[nodeId]/[seq]` and the names of cross-traffic packets in the form `/data/[serverId]/[seq]`.

[2]https://github.com/phylib/PI-Scenario

4.2. Results

The results of our simulations show that the performance of Persistent Interests (PIs) is comparable to the pre-requesting data approach in terms of QoE. Independent of the used network-level queuing strategy, both approaches perform similar. Regarding QoE, those two approaches perform significantly better than the classical NDN approach. As Figure 2 shows, the estimated MOS values are between 0.5 and 1.0 lower for the classical NDN approach, when using the extended Best-Route forwarding strategy. All figures in this section depict 95% confidence intervals resulting from 40 simulation runs per setting. The solid red line in Figure 2 represents the theoretical upper bound of the MOS value, resulting from the simplified E-Model for the G.711 codec in the used setting without packet loss and zero network delay. The upper bound stays below the optimum MOS value of 5 because quantization and equipment impairments are considered in this model.

When focusing on network-level queuing only, we observe that using different queuing strategies has a significant influence on the estimated quality. The scores of Priority Queuing in byte mode, Weighted Fair Queuing and Fair Queuing in byte mode are only marginally below the theoretical upper bound. The good performance of Priority Queuing was expected, because it tries to deliver voice packets regardless of the consequences on the cross-traffic. Weighted Fair Queuing achieves the same quality without being greedy and neglecting the lower-priority cross-traffic. Fair Queuing also achieves a good result without explicitly prioritizing voice packets. Further investigations show that the numbers of received cross-traffic packets are lowest at Priority Queuing and RED. All other queuing strategies do not lead to significant degradation of cross-traffic quality.

Another observation is that the MOS values are higher for

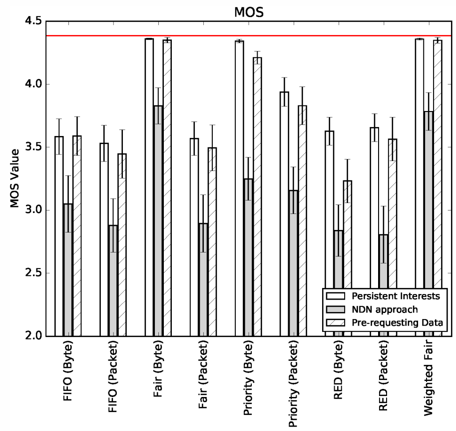

Fig. 2. Estimated MOS of the analyzed approaches. The solid red line visualizes the theoretical upper bound.

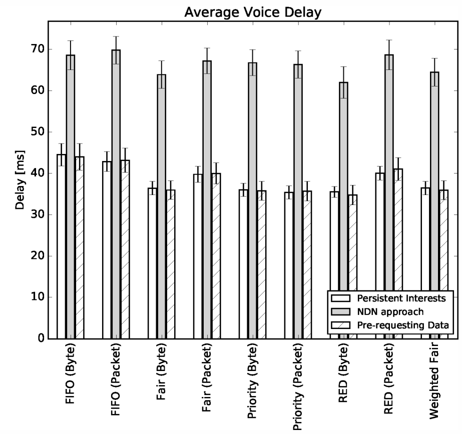

Fig. 3. Average delay in milliseconds between generation and delivery of voice packets.

byte mode queuing strategies. This is explained by the fact that the packet size of voice packets is very small compared to the size of cross-traffic packets. It is more likely that a small packet fits into a nearly full queue compared to larger packets at byte-wise queuing. This means that voice packets are less likely to be dropped with byte-wise queuing, which leads to a higher MOS value.

High delay is one of the most annoying disturbances for Internet telephony and therefore an important variable in the E-Model. Figure 3 shows the elapsed time between the generation of a voice packet and the delivery at the client. Lost packets are not considered in the delay calculation, but however have a negative influence on the estimated MOS value. The figure clearly shows that the use of Persistent Interests reduces the delay from about 70 ms in the classical approach down to about 40 ms, which is a reduction of about 40%.

As Figure 2 shows, queuing has a significant influence on the MOS value of the voice streams. This is explained by different packet-loss rates for different queuing strategies. As Figure 3 shows, the influences of queuing on the delay between generation and delivery of Data is nearly insignificant.

As already observed in [4] in a small scenario, we also measured that the total number of packets and the overall traffic is reduced by the use of PIs. Figure 4 displays the total number of received voice packets, including Interest and Data packets, on the left and the total received megabytes, caused by voice traffic, on the right. PIs outperform the other two approaches in these figures. The number of sent packets is reduced by about 50 %, the overall traffic is reduced by about 20 %. This is due to the nature of PIs. The fact that not every single Data packet is requested by a single Interest leads to an enormous decrease in the number of sent Interest packets and therefore a reduced total number of sent packets. The differences in the number of received packets under different queuing strategies in Figure 4 are caused by higher packet-loss rates in some queuing strategies. As an example, the loss rate is high when using RED as network-level queuing strategy, therefore the total number of packets is lower than for WFQ, which has a low loss rate.

When considering packet loss, it is a crucial difference if a Data packet or a refresh PI is lost. If one or multiple refresh PIs in a row are lost, the lifetime of the installed PIs may time out and voice streams interrupt. We expect that the interval between refresh PIs is crucial for the number of interrupted voice streams. Therefore, we conduct additional simulations using the same scenario, however, varying the Refresh Interval (RI) of PIs. We set the RI to 1, 1.5, 2 and 4 seconds at a constant PI lifetime of 5 seconds, which varies the tolerance for lost PIs. At a RI of 4 seconds a voice stream would interrupt if one PI were lost, a 1 second RI tolerates three consecutive lost PIs. We define an interrupt as 100 or more consecutive lost Data packets, which leads to a voice stream interrupt of at least one second in the case of our employed G.711 setting. Figure 5 shows the total number of interrupts over all 20 phone calls after 150 simulation runs. The results provide two insights: *i*) When using byte-wise network level queueing strategies, nearly no PIs are lost, which is due to their advantage resulting from their smaller packet sizes compared to other packets. *ii*) Using packet-wise network-level queuing, having no fault tolerance (4 seconds RI) leads to a high number of interrupts. Therefore the RI setting should provide a certain degree of fault tolerance. In general, tolerating one lost PI decreases the number of interrupts. Allowing two consecutive lost PIs (1.5 seconds RI) is a good choice for our scenario because additional fault tolerance only leads to minor improvements. Decreasing the RI further reduces the number of interrupts, but increases the number of sent Interests and therefore the overhead.

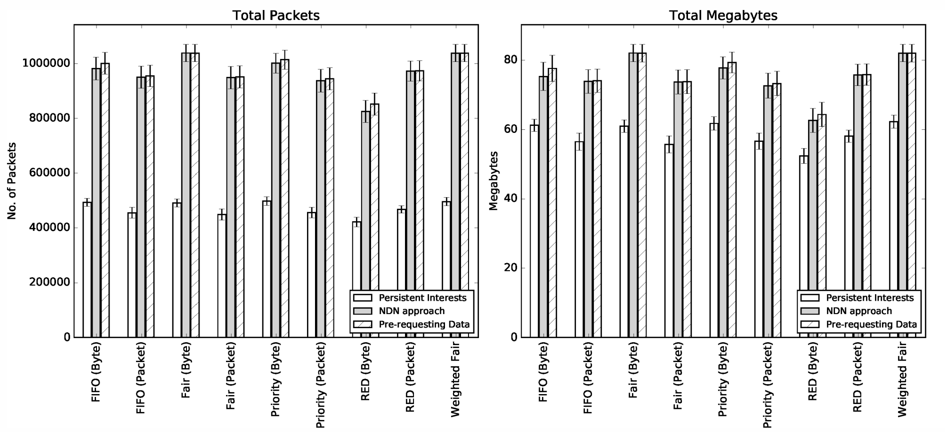

Fig. 4. Average number of total received packets and megabytes including Interests and Data packets of voice traffic

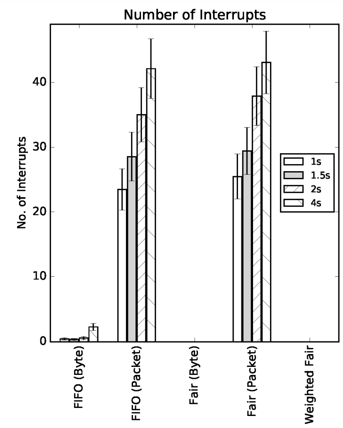

Fig. 5. Average number of interrupted voice streams

5. CONCLUSION AND FUTURE WORK

In this article we investigated push-based traffic, realized by Persistent Interests (PI) in NDN. We compared the performance of PIs to the classical NDN approach and to Jacobson's [5] improvement for conversational services. Our simulations show that PIs perform better than the classical NDN approach and similar to Jacobson's improvement concerning Internet telephony. Further, PIs reduce the network traffic generated by Internet telephony by about 20%, and the number of sent packets by about 50%, which is due to the reduced number of sent Interests. Therefore, all network devices need to handle fewer packets. Handling Interests in NDN is expensive in terms of processing, e.g, including tasks like loop detection, calculating forwarding decisions, etc. Through the use of PIs, the number of sent Interests is drastically reduced, which unburdens network devices. In future work, we will focus on forwarding strategies for PIs under link failures and observe further parameters influenced by PIs, such as CPU load and PIT size on physical hardware [17].

We further showed that network-level queuing in NDN has a significant influence on the service quality. Our results indicate that byte-wise queuing strategies are advantageous for NDN, because Interests are less likely to be dropped due to their small packet size compared to Data packets. The source code resulting from this paper is open-source and available on GitHub (https://github.com/phylib/PI-Scenario).

6. REFERENCES

[1] J. Rosenberg, H. Schulzrinne, G. Camarillo, A. Johnston, J. Peterson, R. Sparks, M. Handley, and E. Schooler, "SIP: Session Initiation Protocol," RFC 3261, Network Working Group, June 2002.

[2] B. Ahlgren, C. Dannewitz, C. Imbrenda, D. Kutscher, and B. Ohlman, "A survey of information-centric networking," *IEEE Communications Magazine*, vol. 50, no. 7, pp. 26–36, July 2012.

[3] L. Zhang, A. Afanasyev, J. Burke, V. Jacobson, kc claffy, P. Crowley, C. Papadopoulos, L. Wang, and B. Zhang, "Named Data Networking," *ACM SIGCOMM Comput. Commun. Rev.*, vol. 44, no. 3, pp. 66–73, July 2014.

[4] C. Yao, L. Fan, Z. Yan, and Y. Xiang, "Long-Term Interest for Realtime Applications in the Named Data Network," in *AsiaFI 2012 Summer School*, Kyoto, Japan, 2012, ACM.

[5] V. Jacobson, D. K. Smetters, N. H. Briggs, Michael F. Plass, P. Stewart, J. D. Thornton, and R. L. Braynard, "VoCCN: Voice-over Content-Centric Networks," in *Proceedings of the 2009 Workshop on Re-architecting the Internet*, New York, NY, USA, 2009, ReArch '09, pp. 1–6, ACM.

[6] "G.107 - E-model: a computational model for use in transmission planning," Tech. Rep., International Telecommunication Union, Jun. 2015.

[7] C. Tsilopoulos and G. Xylomenos, "Supporting diverse traffic types in information centric networks," in *Proceedings of the ACM SIGCOMM Workshop on Information-centric Networking*, New York, NY, USA, 2011, ICN '11, pp. 13–18, ACM.

[8] D. Posch, B. Rainer, and H. Hellwagner, "Towards a Context-Aware Forwarding Plane in Named Data Networking supporting QoS," *ACM SIGCOMM Comput. Commun. Rev.*, vol. 47, no. 1, pp. 9, Jan. 2017.

[9] B. Dekeris, T. Adomkus, and A. Budnikas, "Analysis of QoS assurance using weighted fair queueing (WQF) scheduling discipline with low latency queue (LLQ)," in *28th International Conference on Information Technology Interfaces*, 2006, pp. 507–512.

[10] A. Afanasyev, I. Moiseenko, and L. Zhang, "ndnSIM: NDN simulator for NS-3," Technical Report NDN-0005, NDN, October 2012.

[11] D. Posch, B. Rainer, and H. Hellwagner, "SAF: Stochastic Adaptive Forwarding in Named Data Networking," *IEEE/ACM Transactions on Networking*, vol. 25, no. 2, pp. 14, Apr. 2017.

[12] A. Medina, I. Matta, and J. Byers, "BRITE: A Flexible Generator of Internet Topologies," 2000, Boston University.

[13] International Telecommunication Union, "G.711: Pulse code modulation (PCM) of voice frequencies," 1990.

[14] Bundesnetzagentur, "Dauer Handy-Telefonate," www.bundesnetzagentur.de/SharedDocs/Pressemitteilungen/DE/2011/110728DauerHandygespraeche.html, 2011, Accessed: 2017-01-09.

[15] L. Sun, I. Mkwawa, E. Jammeh, and E. Ifeachor, *Guide to Voice and Video over IP: For Fixed and Mobile Networks*, Springer, 2013.

[16] 3rd Generation Partnership Project (3GPP), "3GPP TS 23.203: Policy and Charging Control Architecture," Dec. 2016.

[17] B. Rainer, D. Posch, A. Leibetseder, S. Theuermann, and H. Hellwagner, "A Low-Cost NDN Testbed on Banana Pi Routers," *IEEE Communications Magazine*, vol. 54, no. 9, pp. 6, Oct 2016.