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Peter Kietzmann, Cenk Gündogan, Thomas C. Schmidt, Oliver Hahm,  
Matthias Wählisch

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# The Need for a Name to MAC Address Mapping Towards Quantifying the Resource Gain

Peter Kietzmann  
HAW Hamburg  
peter.kietzmann@haw-hamburg.de

Cenk Gündoğan  
HAW Hamburg  
cenk.guendogan@haw-hamburg.de

Thomas  
HAW  
t.schmidt@

Oliver Hahm  
INRIA  
oleg@riot-os.org

Matthias Wählisch  
Freie Universität Berlin  
m.waehlich@fu-berlin.de

## ABSTRACT

In this paper, we start from two observations. First, many application scenarios that benefit from ICN involve battery driven nodes connected via shared media. Second, current link layer technologies are completely ICN agnostic, which prevents filtering of ICN packets at the device driver level. Consequently, any ICN packet, Interest as well as Data, is processed by the CPU. This sacrifices local system resources and disregards link layer support functions such as wireless retransmission. We argue for a mapping of names to MAC addresses to efficiently handle ICN packets, and explore dynamic face-based mapping schemes. We analyze the impact of this link-layer adaptation in real-world experiments and quantitatively compare different configurations. Our findings on resource consumption, and reliability on constrained devices indicate significant gains in larger networks.

## CCS CONCEPTS

- **Networks** → **Layering**; *Naming and addressing*;

## KEYWORDS

ICN; NDN; Internet of Things; wireless; link layer

### ACM Reference Format:

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## 1 INTRODUCTION

Named-data networking (NDN) has the potential to improve performance of application scenarios that connect devices via lossy media such as radio. By providing (in-network) caching

on the network layer, NDN helps to on the data link layer by placing co which leads to reduced hop-counts a loss on the application layer. How communication, there is no clear name and a MAC address. This oft multicast) frames on the *data link* mapping prevents ICN from being

Broadcasting on the data link la; tribution but also introduces two frames are not filtered by common work interface card (NIC). They ar which conflicts with limited hardw. CPU, memory, and energy. It is w nodes in a network can provide c of low-end hardware capabilities [1 layer technologies such as 802.11 and error handling of broadcast frames is not even supported in 802.15.4. differences on the data link layer c rent solutions address these proble either implement an NDN-specific error-resilience [9, 10, 18, 20] or, m rent device drivers to implement na NIC [17]. A dynamic mapping of to NDN faces [7, 19] is not sufficien question on how well broadcast c This surprisingly unsatisfying stat revisit the problem and solution sp

In this paper, we investigate ho solutions and design options impac periments, we conduct micro bench devices to better understand the MAC address-to-face mapping. O tributing L2 packets via unicast in to significant performance gains wit resources. The objective of this p discussion starter to find a common distribution on both the network lay

The remainder of this paper is : Section 2, we discuss the problem sp For the case of dynamic face maj design space in more detail in Se measurements in Section 4, and coi

## 2 PROBLEM SPACE AND RELATED WORK

### 2.1 The IoT Use Case

The Internet of Things gathers a diverse set of very heterogeneous nodes. Our focus is on low-end IoT devices, equipped with hardware resources of class 2 [8], connected via radio, and powered by battery. These devices benefit from NDN in the following way. First, the lightweight NDN network stack requires less memory compared to the current IoT stack standardized in the IETF. It is worth noting that cache sizes are independent from network stack sizes. NDN provides off the shelf name-based management and monitoring capabilities, without introducing dedicated services on top of the network layer. Second, those devices may offload data to more powerful nodes without the burden of additional protocols. This is implemented natively on the network layer, and thus simplifies application programming. Third, this in-network caching allows nodes to sleep longer, reduce data delivery latency, and increase content availability [13].

It is worth stressing that the IoT does not only gather different nodes among different operators but may also be heterogeneous within a single domain. As such, we cannot assume that all nodes provide the same set of services, neither on the application, nor on the network layer.

### 2.2 Current Solutions and Challenges

**2.2.1 NDN-specific Link Layer.** Shi *et al.* [18], Grassi *et al.* [9, 10], and Wang *et al.* [20] argue for a link protocol that is specific to NDN. Shi *et al.* [18] introduce NDNLP, which features fragmentation and reassembly as well as acknowledgement and retransmission of packets. NDNLP is located between the network layer (*e.g.*, NDN) and the virtual (*e.g.*, tunnels) or physical (*e.g.*, Ethernet) link layer. Grassi *et al.* [9, 10] present a link adaptation layer, which is tailored for vehicular networks but follows conceptually the same idea as NDNLP. Similarly in the context of improved reliability, Wang *et al.* [20] introduce an NDN broadcast protocol, which tries to minimize collision. Both approaches aim for an increased packet delivery ratio by measures below the application and network layer but still require packet processing by the CPU, independent whether a specific NDN service bound to the broadcast packet is available or not.

**2.2.2 Name-based Filtering on NIC.** Shi *et al.* [17] propose name-based filters on the device driver level of the network interface card. To optimize the implementation for limited on-chip memory of the NIC, names are maintained in a Bloom filter table. This approach exhibits good performance results but comes with the drawback of a layer violation. The data structure to implement filtering is specific to the ICN approach above the link layer. However, not all ICN approaches follow the same naming scheme [4, 21]. Consequently, changing the specific ICN network stack may require update of the device driver. This will slow down deployment of upcoming approaches. More importantly, this approach distributes data via layer 2 broadcast frames, and thus does not benefit from error handling on this layer.

**2.2.3 Unicast Faces.** Approaches to the problem of the link layer or device driver level are proposed by Teubler *et al.* [19] and Baccelli *et al.* [20]. These approaches include unicast faces. Basically, unicast faces are MAC addresses to NDN faces. These are used to filter out partial Interests are broadcasted, containing the MAC address of the sender. Having the MAC address of the sender, the receiver makes use of the source MAC address to filter out the unicast face. NDN packets which are not filtered out by the unicast face conversely include the unicast face. NDN packets which are not filtered out by the unicast face both native MAC-based filtering and unicast faces are suitable for specific adaptations to link layer services, and in case not all nodes within a broadcast domain have the same network layer services, such as unicast traffic reduces data redundancy. A detailed analysis of unicast faces and broadcast on the system load and system overhead is not present. In this paper, we argue for unicast faces and MAC-layer mapping. There are several scenarios in which a reduced system load output is achieved. Our analysis in Section 4 is a first step.

## 3 DESIGN SPACE BY INSIGHTS FROM AN EXISTING LINK LAYER

An NDN node can send Interest packets via unicast or broadcast on the link layer. In this paper, we discuss pros and cons of each approach. In Section 4, we perform a first experimental reality check on the need for link layer support.

For the sake of clarity, we focus on unicast faces and unicast faces on NDN nodes with a single interface connected to the network via shared media. Extending this to multiple interfaces does not change the results. In Section 5, more, we do not explicitly discuss multicast. First, typical lower layer IoT protocols do not support multicast. Second, link layer mapping of MAC address instead of a unicast MAC address to group address mapping is not supported.

### 3.1 Broadcast or Unicast for Interest

**Case 1: Interest Broadcast, Data Delivery.** Within the broadcast domain will be used to deliver data as link layer broadcast. As link layer broadcast, using name prefix in the forwarding table to filter these (successfully received) Interests. Consequently, as soon as a correct Interest is transmitted within the broadcast domain will forward this data packet traffic. This highest level of redundancy is not needed. Practically, in a densely connected network, data delivery, as well as system overhead, content. However, this level of packet redundancy is excessive overhead for each node (*e.g.*, system overhead) also for the complete network (*e.g.*, system overhead). Interferences should be considered e

broadcast traffic, as there is no protective repair of errors on the link layer.

*Case 2: Interest Broadcast, Data Unicast.* Similar to case 1, all nodes of the broadcast domain will create a PIT entry after receiving an Interest packet. However, data packets are directed to the unicast MAC address which is associated with the corresponding outgoing face (*i.e.*, the MAC address of the next hop). As we assume a shared media, all other nodes within radio reach receive the data packet, as well, but drop it at the device driver level because of an unmatching (unicast) MAC address. Those nodes can neither cache nor forward the data on the network layer. Previously created PIT entries will thus not dissolve by receiving data but by timeouts. These PIT entries require memory, processing time and will not help to achieve redundancy. To cope with node failures, an additional mechanism is needed to keep the MAC-face assignment in sync with the MAC address of an alternative next hop.

*Case 3: Interest Unicast, Data Unicast.* Compared to the previous scenarios, in this case, Interest as well as data packets are sent to a unicast MAC address, using unicast faces as described in Section 2.2.3. Such an approach implements hop-by-hop forwarding on the link layer and prevents redundancy completely because any overheard packet is dropped by the network interface card. This setup requires active maintenance of MAC-to-face mapping in case of node failures.

In contrast to Case 2, updating only the unicast data face is not sufficient. Data will be forwarded based on PIT entries. The strong coupling of Interest and data flow requires that the MAC address assigned to the Interest face is in line with the data face. However, usually there is a time gap between sending Interest and forwarding corresponding data. A unicast MAC address that is valid during Interest submission might be outdated when data is forwarded. On the other hand, this case reduces radio transmissions and CPU processing to a minimum and fully incorporates MAC layer retransmission handling.

*Case 4: Interest Unicast, Data Broadcast.* The last case provides very limited redundancy. Data packets will be processed by the NDN stack of all nodes of the broadcast range. However, as Interest has been delivered via MAC unicast, only one node in the broadcast domain created a PIT entry. All other nodes will thus drop the data packet at network layer.

*Discussion.* Case 1 promises path and data redundancy but comes to the cost of excessive resources consumption which may be harmful, especially in IoT networks. Case 2 optimizes data transport via unicast but keeps forwarding redundancy and superfluity of a routing protocol. Case 3 fully optimizes resource overhead and transmission robustness which is promising for battery driven, constrained nodes. However, this approach requires a reliable routing mechanism since it minimizes path redundancy as well caching capabilities. Case 4 brings little benefit to NDN, as redundant data is not utilized.

|           |      |                          |
|-----------|------|--------------------------|
|           | Data | Broadcast                |
| Interest  |      |                          |
| Broadcast |      | 12.1 % ( <i>Case 1</i> ) |
| Unicast   |      | 3.3 % ( <i>Case 4</i> )  |

**Table 1: Unsatisfied Interests with address mappings under presence of li**

### 3.2 The Case for Link Layer

*Experimental Exploration.* In this experiment, we want to check back on the effect of a link layer by counting incomplete Interest-data packets. We select three nodes within radio reach in the FIT IoT-Lab testbed (see Section 2.1). Each node requests 1000 content items from one of two Interests per second (without overlapping) without installing different MAC layer mappings. This generates side traffic on the same radio channel of 50 Bytes within random intervals.

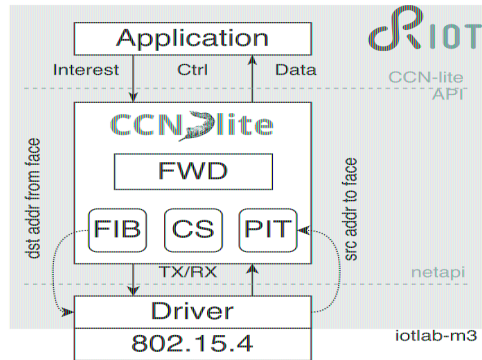
*Results.* Table 1 presents unsatisfied Interests as an indicator of packet loss. Interestingly, we see that broadcasting Interests results in a higher Interest-data rate by about one order of magnitude. Broadcasting data after Interest submission, which we account to an implicit retransmission in the presence of a periodic radio channel, is retransmitted on the MAC layer until the transfer succeeded. Data is then forwarded immediately and thus takes less time (Case 2 versus Case 4). Broadcasting (Case 1) combines these two sources of loss. We conclude that NDN benefits from utilizing the support of MAC layer mappings.

## 4 EXPERIMENTAL EVALUATION

The objective of our experiments is to evaluate the effects through different MAC layer mappings in an IoT environment. Thereby, we make use of typical IoT hardware and radio transmission technologies. We focus on Case 3 (see Section 3) because CC data transmissions via broadcast in

### 4.1 Basic Testbed Setup

All experiments are conducted in the testbed to reflect common IoT properties. It consists of several hundreds of class 2 devices (Cortex-M3 MCU, 64 kB of RAM and an IEEE 802.15.4 radio (*i.e.*, Atmel radio card provides basic MAC layer support in hardware, such as ACK handling and CSMA/CA). For power measurement, we use a consumption monitoring tool of which the resolution time is 332  $\mu$ s and averaging



**Figure 1: System environment: Integration of RIOT and CCN-lite to implement dynamic broadcast and unicast faces in NDN.**

software platform is based on RIOT [6] and the CCN-lite network stack [1], which we include as a third party library in RIOT. The integration of CCN-lite into RIOT and its default components are visualized in Figure 1.

We use default configuration parameters in RIOT and CCN-lite where possible and not mentioned otherwise. In detail, we deploy RIOT release 2017.01 and CCN-lite master with latest updates from May 10, 2017. For our measurements, we configure CCN-lite with a maximum of three Interest retransmissions and 12 seconds Interest timeout. MAC configurations of the radio devices enable IEEE 802.15.4 ACK requests for unicast traffic with a maximum of four retransmissions, and CSMA with a maximum number of four retries, introducing random delays after denied channel access (see [5] for further default values).

The subsequent experiments include single-hop and multi-hop scenarios, which we describe in more detail next to the analysis of our experiments. Our results represent averages over multiple runs with the same parameter settings.

## 4.2 Single-hop Scenario

**4.2.1 Configuration.** We deploy our single-hop measurements at the *Lille* site of the FIT IoT-LAB testbed because all nodes are located in the same broadcast range. We randomly select a single consumer node and a varying number of producer nodes for different measurement runs. Each producer is equipped with a different number of unique and static content items. In all subsequent scenarios, the consumer requests existing content items randomly. We measure the number of system wakeups and the CPU load of both the CCN-lite software stack and the radio device driver.

To implement single-hop data exchange on the data link layer and the network layer, all nodes need to be in physical reachability and consumers need to have routing entries that reach the producers directly. To consider common scenarios, we analyze three basic configurations. (i) On *all nodes*, we install a common prefix route that covers all content names,

and the corresponding face refers to the producer. Note, in this case, a unicast MAC address is used. (ii) For the ability of arbitrary content items via broadcast faces, we install dedicated FIB entries for each producer and consumer, which refer (ii) either to the producers or (iii) to the broadcast face.

Furthermore, to analyze different scenarios, we vary the number of producer nodes and the number of content items per producer in a production scenario.

**Variable network size.** The number of nodes in the network is fixed but we increase the number of content items per producer and vary the different parameter settings. We increase the content request rate per producer and vary the number of content items sent by the consumer increases the number of nodes in the network.

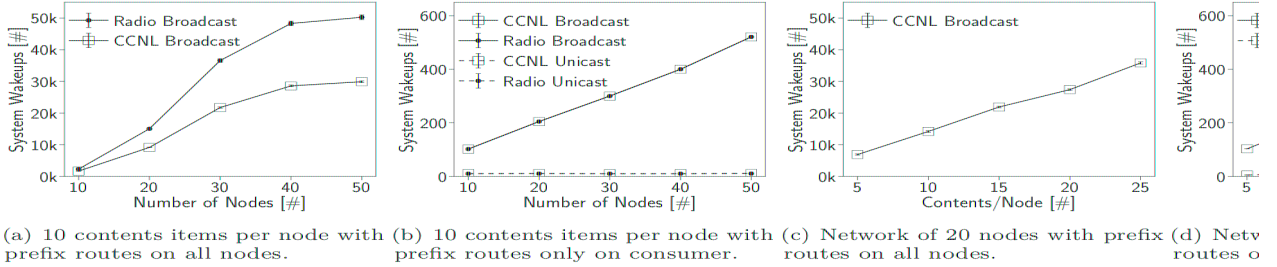
**Variable number of contents items.** The number of nodes is set to 20 and the number of content items per node is increased over different measurement runs. We keep a constant content request rate at 1 request per second.

**4.2.2 Results.** Figure 2 shows the number of requests per producer for the single-hop scenario for different network sizes and a fixed number of content items (see Figures 2(a) and 2(b)), as well as for different network sizes and variable number of content items (see Figures 2(c) and 2(d)). Figures 2(a) and 2(b) show the number of requests per producer where Interests are sent to the broadcast face. Figures 2(c) and 2(d) show the number of requests per producer where Interests are sent to the unicast face. In the broadcast setup, all nodes have routing entries for all content items, which maps faces to the address of each content producer or to the broadcast face. Correspondingly, Figure 3 represents the resource usage we measured.

In terms of energy and processing overhead, it is visible that faces with unicast MAC addresses require less energy than broadcast faces. While the number of requests per producer is constant for varying network sizes, the energy consumption increases with relation to the number of provided content items. This is due to the relation with unicast mapping. Broadcast mapping requires more energy with the number of nodes and the number of content items per node, thus it directly correlates with the number of requested content items in the whole network. This increases resource consumption.

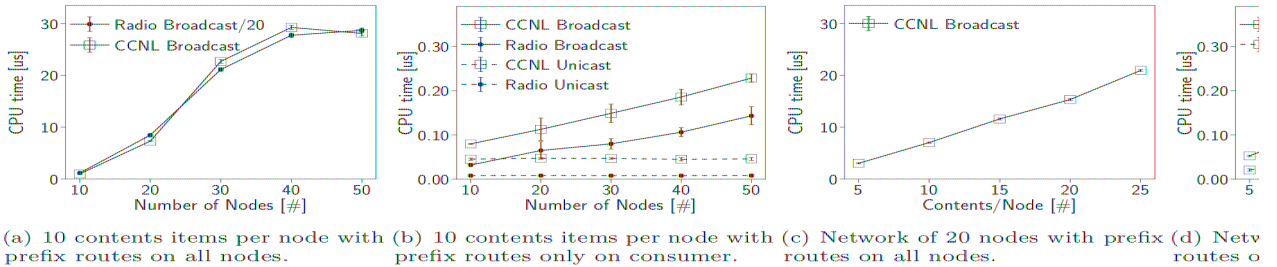
To summarize, unicast faces can reduce the energy consumption of battery driven IoT devices by keeping the processing overhead at a minimum, benefiting from built-in MAC layer traffic, such as ACK handling and other hand, it requires a maintenance of MAC addresses to faces by omitting built-in content replication and alternative data paths.

Deploying common prefix routes for all content items reduces the overall performance, as each node in the broadcast scenario has to wake up during incoming Interests, leading to a higher energy consumption.



(a) 10 contents items per node with prefix routes on all nodes. (b) 10 contents items per node with prefix routes only on consumer. (c) Network of 20 nodes with prefix routes on all nodes. (d) Network of 20 nodes with prefix routes only on consumer.

Figure 2: Number of system wakeups for varying network setups.



(a) 10 contents items per node with prefix routes on all nodes. (b) 10 contents items per node with prefix routes only on consumer. (c) Network of 20 nodes with prefix routes on all nodes. (d) Network of 20 nodes with prefix routes only on consumer.

Figure 3: Absolute CPU usage for varying network setups.

packets that will not be satisfied, as well as data packets that might be received as a consequence of the forwarding mechanism. This leads to an excessive number of wakeups of all nodes in the domain as well as additional data transmissions. The overhead in this broadcast scenario is several orders of magnitudes higher than that of unicast.

To better understand the overhead introduced by broadcast Interest forwarding when all nodes store FIB entries, Figures 2(a) and 2(b) present wakeups, which are separately shown for the radio device and the CCN-lite (CCNL) network stack. In a setup consisting of a single application, single network stack, and a single network interface, both measurements should be roughly equal as the link layer forwards each broadcast packet up to the network stack and vice versa. This holds only in case of a single forwarder (see Figure 2(b)). We detect a much higher number of wakeups by the device driver when all nodes store routes. The impact on CPU times is worse by a *factor of 20*, as depicted in Figure 3(a). We assume radio channel saturation causing this increased resource consumption. To further back these observations, we also measured (on the same network scale) (i) the rate of unsatisfied Interests (0 – 50 %), (ii) radio statistics from which we compute the rate of unsuccessfully transmitted packets due to failing CSMA/CA channel access (0,39 – 0,56), and (iii) the average number of network layer retransmissions (2 – 9 %). All these observables indicate a negative impact on network utilization while broadcasting.

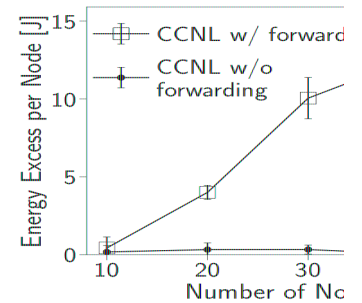


Figure 4: Average energy excess per node and without common prefix routes.

Figure 4 displays the energy per node assumed when Interests are broadcasted without forwarding. The energy excess of *Interest broadcast, data unicast* and *Interest forwarding* over an *Interest unicast* increases with the number of nodes. By comparing Figures 2(a) and 2(b), and Figure 4, it can be seen that the energy consumption with forwarding exceeds single orders of magnitudes, for increasing (single hop) network sizes.

### 4.3 Multi-hop Scenario

**4.3.1 Configuration.** We conducted experiments in *Grenoble*. This site of the test

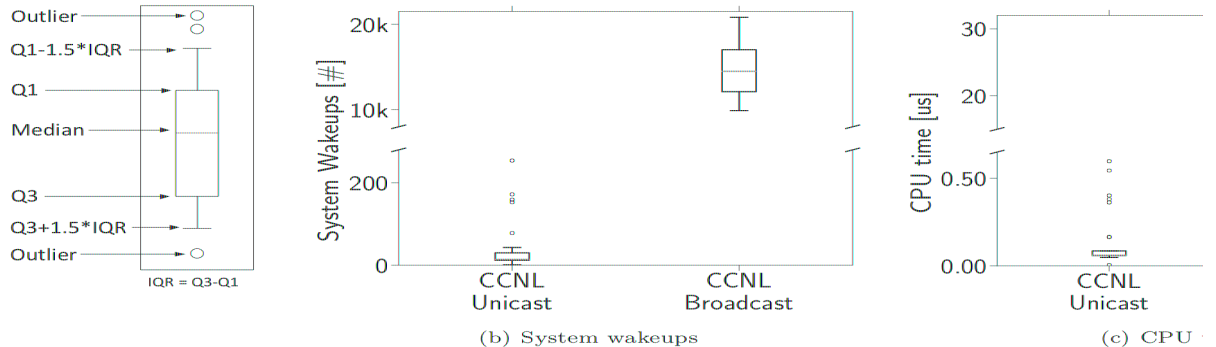


Figure 5: Network of 30 nodes w/ 20 producers and 10 contents items per producer

of nodes such that nodes do not form a single broadcast domain. However, fluctuating properties of the wireless media (*e.g.*, reflections) may lead to changing topologies from multi-hop to single-hop. To ensure a minimal multi-hop connectivity, we introduce a monitoring phase before our experiments start which is based on the mechanism proposed in [11]. During this phase, we identify a set of nodes that inter-connect over multiple hops. The resulting topology consists of 30 nodes where one node acts as consumer, 20 nodes act as producers with a distance of three hops towards the producer, and other nodes serve as intermediate nodes on the path.

Similar to the single-hop scenario, leaf nodes of the resulting topology are equipped with unique content items that are requested by a single consumer in randomized order. Referring to the single-hop experiments, we compare two mapping schemes from content names to faces at the consumer node and subsequent intermediate nodes: (i) a direct assignment of the next-hop MAC address to the corresponding face on the path to the producer, and (ii) a common prefix route where the corresponding face is mapped to a broadcast MAC address.

Even though the same set of nodes is used for (i) and (ii) we cannot guarantee that the same topology appears within the broadcast scenario, as discussed earlier. We do not consider this as a drawback but rather as an advantage, reflecting real-world properties.

**4.3.2 Results.** In Figure 5, we show the impact of broadcast and unicast faces in a multi-hop network in terms system wakeups and CPU times for a fixed size network and a predefined number of content items per producer. We find similar effects compared to the single-hop scenario, where resource costs for the broadcast mapping (with common prefix routes applied on all nodes) are orders of magnitudes higher than for the unicast mapping. The medians of both wakeups and CPU times correspond to our single-hop measurements but larger errors and outliers are visible. The reason for the outlier is rooted in intermediate nodes. These nodes only forward Interest and data packets on the path between producer and

consumer. In our measurements, links which were stable during the asymmetric link behavior later. This is due to approximately 10 % in the unicast scenario where the unicast approach delivered 100 % of the data via the due redundant paths. The resource cost for unicast address mapping as well as the link layer features such retransmission handling and fresh and stable links. Analyzing the impact of these features will be part of future work.

## 5 DISCUSSIONS AND OUTLOOK

In this paper, we discussed current state-of-the-art interaction between the NDN network layer and the data link layer. In contrast to the current state, which maps IP addresses to unicast MAC addresses, arbitrary broadcast, there is no such mapping in NDN. Without sacrificing the principle of NDN, we argue that link layer broadcast should be a deployment scenario (*e.g.*, IoT), as hardware resources in terms of energy are abundant. We reviewed the current solutions and conducted a first set of experiments in a real-world scenario. We map faces to unicast or broadcast MAC addresses and analyze the resource overhead and the advantages of these functions (*e.g.*, retransmission handling).

The position of this paper is that link layer mapping is needed as a first step. Second, our community should focus on how this does not affect the core of current link layer solutions and benefits from built-in link layer solutions. Third, promising solution, the dynamic creation of faces has been mostly ignored and deserves further research. In this paper, we contributed a first real world testbed and related analysis. We hope that the community will find a common understanding of the interaction between network and data

## A Note on Reproducibility

We explicitly support reproducible research [3, 16]. Our experiments have been conducted in an open testbed. The source code of our implementations (including scripts to setup the experiments, RIOT measurement apps etc.) are available on Github at <https://github.com/inetrg/ACM-ICN-2017>.

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