Forwarding Strategies in NDN-based IoT Networks: A Comprehensive Study

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Abstract. Named Data Networking (NDN) is a new communication model that proposes to shift the manner to do networking by fetching data by names instead of host addresses. This data-driven architecture is considered promising for the Internet of Things (IoT) applications due to its inherent characteristics, such as naming, caching, and stateful forwarding, which give NDN the power to support natively, without adaptation mechanisms, the major requirements of the IoT environments. Nevertheless, particular management should be provided by the forwarding protocols when handling the limited resources of the IoT objects. This paper is devoted to investigating NDN-based forwarding strategies for the IoT, along with a comprehensive comparative study, followed by a simulation of some representative schemes. Insights on the main observations learned from the conducted evaluation are presented in the paper, highlighting the strengths, weaknesses, and suitability of every benchmarked solution in the context of NDN-IoT twinning.

Keywords: Internet of Things · Named Data Networking · Name-based forwarding · Wireless Ad hoc Networks.

1 Introduction

Interconnecting smart resource-constrained objects in the Internet of Things (IoT) is currently mostly supported by IP-based solutions, which rely on the adaptation of the original TCP/IP communication stack to fit IoT basic requirements. Nonetheless, these adaptation efforts have incurred management complexity and overload on the network resources [1].

Recent research have explored the aptitude of the Information-Centric Networking (ICN) paradigm in handling IoT requirements, which proposes to fetch data by names instead of host IP addresses. This new networking technology would provide natural support for the existing IoT applications where data is placed in the first plane.

Named Data Networking (NDN) [2] has been considered as the most prominent instantiation of the ICN, whose key features, namely naming, caching, packet level security, and stateful forwarding, make it very attractive for the IoT ecosystem. In such networks, sharing the same wireless communication medium in addition to the mobility of the nodes constitute a serious challenge to NDN-based forwarding mechanisms, which have to provide smart and lightweight techniques to handle efficiently the unreliable and ad hoc nature of these environments.

Indeed, NDN employs, in addition to the routing decision, a stateful forwarding plane where each node keeps track of received Interests to reply to them later once getting a positive or negative response. Moreover, thanks to its salient features, especially naming and caching, which are manageable directly on the network layer, multicast/anycast forwarding support is provided, hence offering a robust solution to cope with unpredictable topology changes of the IoT networks.

Nevertheless, through a unique external communication interface, imposed by such ad hoc networks, NDN forwarding operation faces a new kind of challenges, especially the broadcast storm phenomenon [3]. This latter problem is not adequately handled by the NDN original machinery, which might cause serious performance degradation to the network. To overcome this new challenge, the research community has devoted an effort axis focused on forwarding solutions, but which is still at a pre-maturing stage [4].

The rest of this paper is organized as follows. Named Data Networking and its peculiarities in IoT networks are introduced in Section 2, with a focus on the NDN forwarding machinery in the context of wireless ad hoc environments. This is followed, in Section 3, by a comprehensive state-of-the-art study on the existing NDN-based forwarding strategies devoted to wireless ad hoc networks in general and IoT in particular. In Section 4, a performance evaluation, via ndnSIM simulation platform, of some representative forwarding schemes is presented, along with an in-depth analysis and discussion. Finally, a conclusion summarizing the main obtained results and the lessons learned is given in Section 5.

2 Named Data Networking in the Internet of Things

NDN architecture proposes, through dissociating the content and its location, to retrieve data directly on the network layer, of the communication stack, by substituting source addresses by application data names. Consequently, this new paradigm leads to the shift of the communication model from location-centric to data-centric.

Two types of packets are used in NDN: Interest and Data. A consumer requests content by sending an Interest packet, which carries the targeted Data prefix name. A Data packet is returned by a producer, or any intermediate node having the requested Data in its cache, in response to that Interest, and follows the reverse path taken by the Interest to reach the consumer.

The structure of an NDN-IoT node is depicted in Fig. 1 which basically incorporates three data structures: the FIB (Forwarding Information Base), the PIT (Pending Interest Table), and the CS (Content Store). This latter is employed to store temporarily Data packets, thus allowing reducing request response time in the network. The PIT is used to save incoming interfaces of pending Interests to respond to them later, thus allowing achieving stateful forwarding feature. Whereas the FIB table contains Data prefix names with the corresponding output faces toward potential content providers. Besides, these three data structures are managed by a Forwarding Strategy engine, namely Ndn Forwarder Daemon (NFD) [5], to make the forwarding decisions about incoming Interest or Data packets.

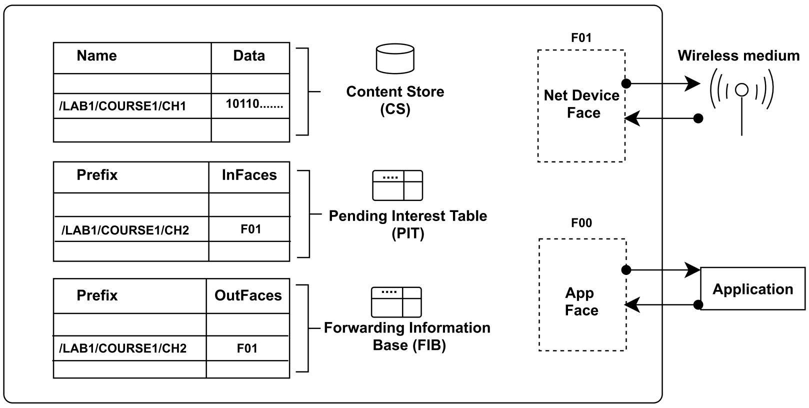


Fig. 1: NDN-IoT Node structure, adapted from [6].

In a NDN-based IoT environment, mostly characterized by wireless ad hoc deployment mode, the basic structure of the NDN node keeps the same form as the infrastructure architecture. Nevertheless, some specific characteristics, due to the wireless communication medium, affect the machinery of its forwarding daemon that faces a new range of challenges, such as broadcast storm problem, or intermittency caused by nodes' mobility in the network.

Furthermore, in such architecture, the NDN node is obliged to share one external ad hoc face with all its neighbors, through which all packet types are exchanged. To cope with this new deal, NFD, in its latest releases, has been updated to support ad hoc communication mode, in addition to the wired mode, by adding specific exceptions in Data and Interest packets management events. We describe in the following some differences between the two communication modes.

For instance, forwarding received packets on the same incoming face has been enabled for both Data and Interest packets in ad hoc communication, since there is one external face. This situation is prohibited in point-to-point (wired) mode, where each communication link has its corresponding face. Besides, sending a Negative ACKnowledgment (NACK) packet is bypassed in ad hoc mode, so even if no valid next-hop exists in the routing table (FIB) of a node, no Nack packet is sent on the Interest incoming face. The reason for that is, as we saw earlier, the targeted content could be brought, to the requester, by another neighbor node having the same ad hoc face (outgoing face in the FIB table). Moreover, in ad hoc communication, when a forwarder node receives a new Interest packet, it keeps it in the PIT table and any subsequent Interest with a similar name is considered a loop (the packet is ignored). Whereas in point-to-point mode, duplicate incoming Interests from the same face is not considered a loop.

In summary, it can be observed that the new and flexible design of NDN architecture, thanks to its key features, especially naming, caching, and stateful forwarding, allows it to handle efficiently the challenging aspect of the IoT environment.

After highlighting NDN's main characteristics in the context of the IoT, specifically its forwarding engine, we will present in the next section the forwarding strategies that have been proposed in the literature.

3 Related work

Many research studies have been devoted to handling forwarding issues in the context of NDN-based wireless ad hoc networks, including the IoT environments.

In [7], the authors present an Interest forwarding strategy based on randomized scheduling timers to reduce packet collisions, while exploiting the geolocation of the nodes to perform a distance-based data forwarding. In [8], a forwarding technique tailored for wireless ad hoc NDN networks is proposed, where Interest forwarding is based on the beacon messages that include the identifier of the sender and a bloom filter carrying the list of all its valid neighbors. Interest packet is further forwarded to nodes that are not included in the incoming bloom filter.

In [9], by drawing on Directed Diffusion protocol [10] principle, an enhancement of NDN forwarding scheme in WSNs is proposed. To do this, the original NDN Data packet has been modified to carry the ID of the sender, which is stored in a new data structure called Next Hop Table (NHT). This latter is exploited by nodes to manage incoming data retrieval queries. In a similar context, the same authors propose in [11] a content-centric architecture (E-CHANET) to handle the multihop wireless issue. In this solution, the node uses a new distance table in forwarding decisions, which stores the provider ID and the distance to the consumer. These two extra information are retrieved from the exchanged Interest and Data packets.

Moreover, a Neighborhood-Aware Interest Forwarding (NAIF) protocol designed for MANETs is proposed in [12], where the eligibility of a forwarder for a given prefix name, among its neighbors, is based on its content retrieval rate for that Interest and its distance to the consumer. Whereas in [13], a direction-selective forwarding strategy for content retrieval is proposed in a mobile cloud computing architecture, where the geographical coordinates of the neighbors are used by a forwarder node, in addition to new packet types (ACK and CMD), to select the relay nodes from the four quadrants of its transmission range.

On the other hand, authors in [14] designed a Reactive Optimistic Name-based Routing (RONR) mechanism, which minimizes the number of radio communications in IoT environments. For this purpose, only the first Interest query flooding is performed in the network, while the subsequent requests for the same prefix follow the footsteps, traced by the initial Data response, which are stored in the FIB table of the relay nodes.

Additionally, a Geographic Interest Forwarding (GIF) scheme for NDN-based IoT is proposed in [15]. In this solution, the nodes in the network discover their neighbors by means of HELLO messages, which include the ID of the node and its coordinates. Before sending Interest requests, a Producer Discovery phase is performed by the content producers to announce their availability to the potential consumers.

Besides, authors in [16] proposed a dual-mode Interest forwarding scheme (DMIF) for NDN-based WSNs, where both flooding and directive forwarding modes are used by the nodes in the network according to the FIB lookup for the incoming Interests. To manage Interest flooding, a TTL value is added to the Interest packet, which is dynamically tuned according to the network needs. A deferred timer is additionally used in Interest and Data forwarding phases, to counteract the broadcast storm problem in wireless communications.

In another research work [17], a hybrid forwarding strategy is proposed in wireless ICN, where an Ad hoc Dynamic Unicast (ADU) communication mechanism has been designed based on MAC notifications, allowing a dynamic alternation between unicast and broadcast modes. To achieve this, MAC addresses are disseminated in Data packets and stored in the FIB table, to serve as next-hops for subsequent queries.

While authors in [18] propose a reinforcement learning NDN-based forwarding solution for low-end IoT. The eligibility of a node to forward an Interest packet is based on a waiting time. This latter is calculated according to a cost field, carried in the Interest and Data packets, which jointly reflects the distance to the provider of the node and its eligibility to forward an Interest packet.

Lastly, authors in [19] introduce a Location-Based Deferred Broadcast (LBDB) scheme for ad hoc NDN networks, which relies on a transmission timer for the Interest forwarding phase. This timer is used to determine the priority of the forwarders and is based on the location information of the nodes and the data providers.

In sum, what we observed from our literature review, is that almost all the proposed forwarding solutions in ad hoc networks do not respect properly NDN native design, where additional fields are added to the original packets (Interest and Data). For instance, identifiers of nodes, and/or extra data structures are employed, to keep information about the network activity. Furthermore, deferred forwarding timers are often used in the proposals to avoid broadcast storm problems, alleviate the network, and improve its performances.

Based on that, and since NDN-based forwarding strategies for constrained IoT networks were not largely explored in the literature, we conduct, in the next section, an evaluation of three representative forwarding solutions, while considering the IEEE 802.15.4 as a wireless medium, by mean the official and the most used simulator in this area. The attempted goal is to assess different forwarding strategies and identify their weaknesses, strengths, and suitability in the context of a wireless-constrained IoT environment.

4 Performance evaluation

We have learned from our previous study, that NDN-based forwarding solutions in IoT resort to the deferred broadcasting and/or modification of NDN primitives to overcome constraints imposed by wireless ad hoc communication links. Thus, we have chosen to conceive and examine the following forwarding protocols: (1) a Blind deferred Interest Forwarding (BF), inspired from [11], which uses collision avoidance timers for the Interest forwarding phase, based on random delays; and (2) a Geographic Interest Forwarding (GF), inspired from [15], which uses geographic coordinates of nodes to perform a greedy forwarding of the Interest packets to the Data providers; in addition to the Native Forwarding mechanism of NDN without modification, which we call (NF).

4.1 Simulation platform and parameters

To this end, ndnSIM [20], the official simulator of the NDN project, is chosen as an evaluation platform, which implements all the basic features of the NDN architecture and reproduces faithfully the holistic functioning of its forwarder engine NFD. Besides, we have selected the IEEE 802.15.4 communication standard, tailored for wireless low-end and constrained IoT, as an underlay to the NDN layer. Concerning the network deployment, we have chosen a grid topology of 25 nodes including one consumer and one producer. The simulation time was set to 100 s, the Interest transmission rate was fixed at 10 p/s, and the transmission range of the nodes was varied from 10 m to 40 m.

Table 1 summarizes the simulation parameters.

Table 1: Simulation parameters.

Parameter	**Value**	**Parameter**	**Value**
NetDevice	LrWPAN (IEEE 802.15.4)	CS size	10
Area size ($m \times m$)	40×40	PIT size	10
Topology-Number of nodes	Grid-25	Interest packet size ($bytes$)	5
Simulation time (s)	100	Data packet size ($bytes$)	10
Interest Transmission Rate ($packet/s$)	10	Transmission Range (m)	10, 20, 30, 40

4.2 Performance metrics

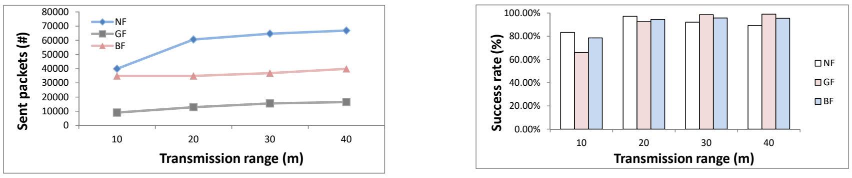
To pinpoint the behavior of the benchmarked solutions in the context of constrained wireless IoT network, we have considered the following performance metrics:

- *Sent packets:* The total number of Interest and Data packets that have been forwarded in the network;
- *Success rate:* The average success rate (satisfied Interests) of the consumers in the network;
- *Hop count:* The average hop count for all Data packets received by the consumers in the network; and
- *Retrieval time:* The average retrieval time of all Data packets received by the consumers in the network.

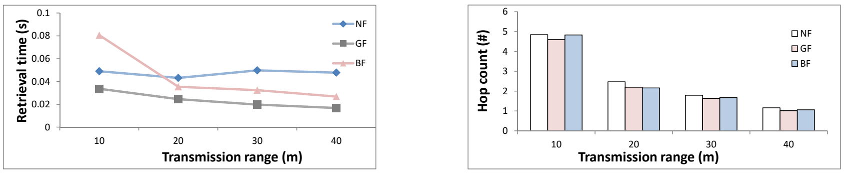
In the sequel, we will discuss the obtained results.

4.3 Obtained results and discussion

The performance metrics collected from the different simulations are depicted in figure 2.



(a) Sent Interest packets (b) Average success rate



(c) Average retrieval time (d) Average hop count

Fig. 2: Impact of the transmission range on the benchmarked solutions.

The simulation results show that the number of sent packets (Interest and Data) in the network is huge in the case of NF, moderate in the case of BF, and very low in the case of GF, for all the transmission ranges (see figure 2a). The reason for this is that GF uses a single forwarding path in the content exploration phase, thanks to its knowledge of the producers' coordinates which allows reaching them optimally without flooding all the network.

Besides, the deferred Interest forwarding of BF permits to reduce the number of transmitted packets by enabling some nodes, having the lowest waiting time, to forward the Interest packets among all their neighbors. These latter, cancel forwarding operation once receiving the same Interest packet, within the waiting period, from the eligible neighbor. Lastly, for its part, without a specific mechanism to counteract the broadcast storm problem, NF floods the entire network by the Interest packets at every Interest transmission phase, which explains its worst performance regarding the number of transmitted packets in the network.

Furthermore, the success rate stats, as shown in figure 2b, reveal that for low transmission ranges values (up to 20m), NF registers the best performances followed by BF and GF respectively; whereas, GF outperforms the two others for higher transmission range values (30m and above). This can be explained by the unreliable wireless communication medium of the IoT, which causes packet loss. Indeed, the probability of success packet transmission is proportional to the transmission range; consequently, in low transmission ranges, one path forwarding scheme of GF will be penalized in terms of packet success rate compared to BF and NF, both of which use multipath forwarding. Nonetheless, for higher transmission range values, GF registered a better success rate than the two others, thanks to the geographic-based greedy forwarding technique which leads to less network overload and thus fewer packet collisions.

Regarding the retrieval time results, figure 2c shows that GF is better than BF and NF for all tested network densities. Indeed, the retrieval time metric is highly related to the induced overload in the network, i.e., the less network traffic, the best retrieval time is. On the one hand, GF exploits geographic-based forwarding to reach Data producers, allowing a reduction in Interest (re)transmissions and collisions, and thus a rapid content retrieval. On the other hand, NF's and BF's repeated Interest broadcast operations, whatever deferred or not, cause packet collisions and extension of their waiting time in the nodes' queues, especially with the concurrent access to the wireless communication medium of the IoT, which leads to important content retrieval delays.

Lastly, the greedy geographic forwarding mechanism of GF led to building optimized paths to the Data providers, hence, ensuring an average hop count to the producers almost equivalent to the two other strategies, which both, with no awareness of network topology, flood the entire network using multipath forwarding to retrieve the content (see figure 2d).

To sum up, the carried-out simulations show that the native forwarding machinery of NF falls in the broadcast storm problem, which was traduced by a huge number of transmitted and redundant packets in the network. Besides, the deferred forwarding technique of BF has allowed reducing flooding the entire network, where the traffic overload has been nearly halved compared to NF. Furthermore using the nodes' geo-coordinates has allowed GF to register better performances than NF and BF, especially in terms of traffic overload and success rate. Nevertheless, despite being closer to host-centric than the data-centric paradigm, this geographic knowledge requires additional modules (e.g., GPS) and extra data storing structures that could incur more complexity and overhead (heaviness) to the resource-constrained IoT nodes.

5 Conclusion

In this paper, we investigated NDN-based forwarding strategies in the IoT. After pinpointing the NDN core principle and its key strengths in handling IoT needs, we analyzed the state-of-the-art forwarding solutions that have been proposed in the literature in this area, along with an in-depth discussion focusing on the different used techniques allowing meeting IoT requirements related to wireless ad hoc environments. This was followed by a comparative study of representative NDN-based IoT forwarding schemes, where simulation outputs revealed that the native forwarding machinery of NDN falls in the broadcast storm problem, which can be reduced by the deferred forwarding technique. Also, the geographic forwarding solution registered almost the best network performances but which, however, could be less suitable to constrained-resources IoT deployments, due to its host-centric nature and the additional network topology knowledge over cost.

All in all, the conducted analysis in this paper shows that a well-designed NDN-based IoT forwarding protocol should be issued from a compromise between different techniques, such as the deferred forwarding and the topology network knowledge, in the aim to handle efficiently the challenging aspects of the IoT environments.

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