


Congestion Control for NDN-Based MANETs: Recent Advances, Enabling Technologies, and Open Challenges

Dimitris N. Kanellopoulos, University of Patras, Patras, Greece

 <https://orcid.org/0000-0002-4147-9295>

ABSTRACT

A mobile ad hoc network (MANET) has several intrinsic features that create unique queuing dynamics, and thus congestion control inside a MANET must be achieved under time-critical conditions. Meanwhile, the Named Data Networking (NDN) architecture ensures traffic optimization and has attracted renewed attention as part of the future internet. The synergy between NDN and MANETs can be exploited in order to improve the performance of dynamic content routing and congestion control mechanisms. This overview identifies the key concepts involved in congestion control for NDN-based MANETs. It also proposes some criteria for categorising existing congestion control solutions for NDN-based MANETs and discusses the advantages and disadvantages of each category. Future challenges regarding congestion control for NDN-based MANETs are also highlighted.

KEYWORDS

Adaptive Forwarding, Congestion Control, Dynamic Content Routing, Mobile Ad Hoc Network, Named Data Networking, Traffic Shaping

INTRODUCTION

End-user computing is a compilation of approaches to computing that allows end-users to better control their mobile computing environment without the aid of real programmers or developers. These approaches (i.e., computer systems and platforms/architectures) can integrate end-users into their mobile computing environment. Such an approach is the Named Data Networking (NDN) architecture for a mobile computing environment that involves mobile software, hardware, and mobile communication. Mobile software deals with the characteristics and requirements of mobile applications, while mobile hardware includes mobile devices or device components. Mobile communication is often based on mobile ad hoc networks (MANETs) and involves specific protocols and intelligent technologies. A MANET is a wireless ad hoc network that is deployed mostly in emergencies like a battlefield and natural disasters as its nodes can communicate with each other without any infrastructure. A MANET is made up of autonomous radio nodes, which form a dynamic,

DOI: 10.4018/JOEUC.20210901.oa6

This article, published as an Open Access article on May 28, 2021 in the gold Open Access journal, Journal of Organizational and End User Computing (converted to gold Open Access January 1, 2021), is distributed under the terms of the Creative Commons Attribution License (<http://creativecommons.org/licenses/by/4.0/>) which permits unrestricted use, distribution, and production in any medium, provided the author of the original work and original publication source are properly credited.

multi-hop radio network in a decentralized way (Sarkar et al., 2013). Nodes themselves cooperatively implement network management. Such cooperation requires detecting routes and forwarding data packets. A MANET relies on the multi-hop type of routing for the data transmission because the destination node is often out of the radio-range of the source node, and some nodes can act as a router to forward data (Kanellopoulos, 2017). In a MANET, each node is a relay for routing content. The intermediate node that becomes the network relay often experiences network traffic overloading. When the intermediate node cannot accommodate the amount of network load that exceeds its capacity, then network congestion occurs (Rath et al., 2017). In such a situation, a congestion control protocol must achieve fairness in network traffic and the efficiency of bandwidth usage. MANETs have the following characteristics (Kanellopoulos, 2019):

- *Problems related to hidden and exposed terminals.*
- *Constraints on resources:* MANET devices work with limited CPU processing capabilities, limited battery life, inadequate bandwidth support, limited storage, etc.
- *Error-prone shared broadcast channel:* The wireless links have a higher error rate, fading, signal interference etc., while the Medium Access Control (MAC) layer algorithm tries to control access to the shared broadcast channel.
- *Nodes mobility:* Nodes are roaming and can only interact with their direct neighbour nodes. The dynamic nature of a MANET results in frequent changing network topology and link breaks. This makes routing more difficult because of the frequent route change/route break leading to loss of connectivity. The routes are updated frequently as the network topology is constantly changing, and this results in an increase in the network traffic.

The characteristics of MANETs (i.e., high channel error rate, severe link-layer contentions, frequent link breakage, and dissimilar path quality-of-service (QoS) properties) seriously interfere with communication. Therefore, these characteristics ultimately degrade the overall performance of MANETs in terms of end-to-end delay, packet delivery ratio, network throughput, and network overhead. Moreover, these characteristics present various challenges in the design of the routing and congestion control protocols and complicate QoS provision. Apart from fairness in network traffic and efficiency of bandwidth usage, congestion control for MANETs requires additional demands because network congestion is not only due to network traffic, but it can also be due to other factors such as node mobility, wireless signal noise, interference, and contention. Additionally, a congestion control protocol for MANETs must be energy efficient and must reduce packet loss retransmission as much as possible to reduce energy wastage on each node (Kanellopoulos & Sharma, 2020).

It is difficult to apply TCP/IP directly to ad hoc networking. TCP/IP is effective in IP networks (like the Internet) but it is not practical in MANETs, because its use results in high packet loss due to network congestion and a high amount of broken links in wireless connection. Even though IP-based routing protocols for MANETs can handle the changes in network topology, these routing protocols cannot support real-time multimedia applications. This happens because IP-based MANETs lack support for advanced networking functions such as multisource and multipath transport, consumer-driven multicast, and on-path caching (Thomas et al., 2020). Multisource and multipath transport can handle source and node failures, while consumer-driven transfers can handle the consumer (source) mobility. Lastly, on-path caching can address potential network partitioning in MANETs. In IP networks, these advanced networking functions are not supported because the content is retrieved by its IP address. The existing Internet architecture adopts the TCP/IP model that is based on the end-to-end principle and perpetual connectivity. In this model, the network is ‘transparent’ and just forwarding data (i.e., it is ‘content unaware’). Due to this unawareness, multiple copies of the same data are repeatedly sent between endpoints on the network without any traffic optimization.

Information-centric networking (ICN) is a network technology for the future Internet architecture that provides traffic optimization (Ahlgren et al., 2012). ICN addresses IP network limitations in supporting content distribution and information access by decoupling content from hosts and providing the ability to retrieve a content object by its identifier (name). Named Data Networking (NDN) is an emerging ICN-based architecture that aims to cope with the increasing traffic demands on the Internet (Saxena et al., 2016). The central feature of the NDN network architecture is the “named content” (or data) and not the “end-host” (Zhang et al., 2014b). Based on the named content, NDN can realize fast content retrieval and delivery. In NDN, connectivity may well be intermittent, while mobility and multi-access are the norms. Also, anycast, multicast, and broadcast are natively supported. Data become independent from location, application, storage, and means of transportation. This NDN property enables in-network caching and replication of content. NDN supports name resolution, dynamic routing, content caching, and traffic optimization. Recently, NDN has been evolving as a suitable network stack solution for MANETs (Amadeo et al., 2013; Rehman & Kim, 2015; Kuang & Yu, 2015; Kim et al., 2016). NDN offers new perspectives on mobile ad-hoc communication because routing is based on names. As every content object has a unique name and is signed, authentic content can be stored and cached by any node. If connectivity to a content source breaks, it is not necessarily required to build a new path to the same source, as content can also be retrieved from a closer node that provides the same content copy. For example, in the case of collisions, retransmissions do not need to be performed over the entire path thanks to caching, but only over the link where the collision occurred. Furthermore, multiple requests can be aggregated to improve the scalability of wireless multi-hop communication. NDN is an ideal architecture for deploying effective congestion control for MANETs. In NDN, congestion control is mostly performed by the receiver (consumer) node because network transport is initiated and controlled by this node.

Motivation

Many congestion control protocols have not emphasized NDN issues at all. Such a challenging area has attracted considerable attention from researchers, which inspired us to conduct a literature survey on congestion control for NDN-based MANETs. This article analyzes and compares existing congestion control protocols for NDN-based MANETs. Such a comprehensive survey does not exist and this is the aim of this article.

The contributions of this survey are the following: (1) It analyzes and surveys the existing congestion control protocols for NDN-based MANETs; (2) It discusses open research areas such as cross-layer design for congestion control.

The remainder of this article is organized as follows: the second Section provides the research methodology and papers selection mechanisms. The third Section explains why NDN is appropriate for MANETs to solve the problem of congestion control. The fourth Section discusses congestion control issues for NDN, while the fifth Section compares congestion control protocols for NDN-based MANETs. The sixth Section presents cross-layer congestion control for NDN-based MANETs. The seventh Section presents shortcomings and open challenges, while the last Section concludes the article.

SYSTEMATIC LITERATURE REVIEW

Articles Selection Method

We provide a Systematic Literature Review (SLR) methodology (Kitchenham, 2004) with particular attention to studies related to congestion control for NDN-based MANETs. The SLR is employed to do a systematic study of congestion control protocols for NDN-based MANETs. We have proposed a research question to deal with the key issues of congestion control for NDN-based MANETs.

Question Formalization

Key issues and challenges in the field are identified. Such issues are receiver-driven congestion control, hop-by-hop congestion control, cross-layer congestion control, and adaptive forwarding in multipath content routing. This study answers the following research question:

RQ: What is the emphasis of congestion control protocols for NDN-based MANETs?

This question determines the number of congestion control studies that have been published to date to emphasize its significance in NDN-based MANETs.

Article Selection Process

The article selection process is performed in three stages:

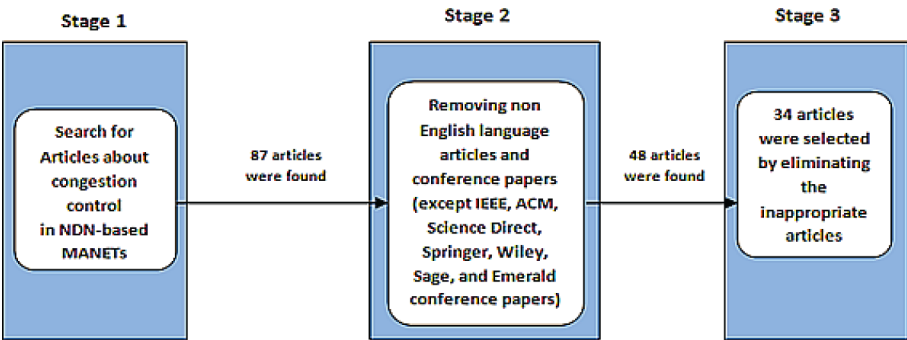
1. Automated keyword-based search;
2. Selection of the article based on the title, abstract, and quality of the publication;
3. Elimination of inappropriate articles.

In the first stage, the search process is automatically performed using searching on popular academic databases such as IEEE explorer¹, SAGE², Google Scholar³, ACM⁴, Wiley⁵, Emerald⁶, Springer⁷, and Science Direct⁸. The following search string was defined by adding other spellings of the main elements to find relevant articles. The search string was:

√ (“MANET” OR “Mobile ad hoc network”) AND (“Information-Centric networking” OR “ICN” OR “NDN” OR “Named Data Networking”) AND (“Congestion control” OR “Routing” OR “Forwarding” OR “Cross-layer”)

We found 87 articles from journals, conference proceedings, books, patents, and theses. These articles were published between 2013 and 2020. In the article selection based on the quality of the publisher stage, the search string is constrained by searching for conference papers and journal articles of IEEE, Sage, ACM, Wiley, Science Direct, Emerald and Springer, to guarantee that only high-quality publications and articles are selected for the review. Consequently, 48 articles are selected. Figure 1 indicates an overview of the process applied for identifying the articles. In the third stage of eliminating the inappropriate articles, a Quality Assessment Checklist (QAC) based on (Kitchenham et al., 2004) is developed where those articles emerging from the initial search are refined. After

Figure 1. Filtering method for found articles



reading abstracts, we eliminated the inappropriate articles. The entire body of the remaining papers was checked and those which were not related to our concerned field were also crossed out. After eliminating inappropriate articles, only 34 studies were identified.

NAMED DATA NETWORKING FOR MANETS

Chen et al. (2016a) compared the fundamental differences between NDN transport protocol and IP transport protocol from three perspectives: user side, routers, and network provider. They also classified recent NDN-based transport control strategies. NDN has evolved as a suitable network stack solution for wireless sensor networks (WSNs) (Jaber et al., 2017), vehicular ad hoc networks (VANETs) (Khelifi et al., 2020), and the Internet of Things (IoT) (Al-Turjman, 2018). Due to the broadcast nature of the wireless channel, a MANET presents severe issues (e.g., packet collisions, flooding, and data redundancy). In this context, Al-Adhaileh et al. (2020) stressed the significance of using NDN in MANETs, while Tariq et al. (2019) provided a detailed survey regarding forwarding strategies in NDN-based MANETs. Muchtar et al. (2019) considered how dynamic content routing must be implemented to achieve useful energy efficiency improvements of the content routing mechanism in an NDN-based MANET. Amadeo et al. (2014a) surveyed critical issues on wireless networking for various content-centric architectures. However, they paid little attention to congestion control for NDN-based MANETs. Existing congestion control schemes (Amadeo et al., 2014b; Li et al., 2016; Li et al., 2017a; Li et al., 2017b) in NDN-based MANETs are incomplete, as they only partially solve the problem of congestion control.

In NDN, data consumers (consumer nodes) enable communication through the exchange of two types of packets (messages): *Interests* and *Data*. Both types of packets carry a name that identifies a piece of data that can be transmitted in one Data packet:

- **Interest:** The name of a wanted piece of data (by the consumer) is put into an Interest packet. This Interest packet is sent to the network. It is forwarded toward the data producer(s) by the routers/nodes.
- **Data:** Once the Interest packet reaches a node that has the requested data, the node will return a Data packet that contains both the name and the content, together with a signature. This signature is the producer's key and binds the content with the producer. This Data packet must get back to the requesting consumer, and thus, it follows in reverse the path taken by the Interest packet.

Data packets mainly contribute to the network traffic, while the forwarding strategy cannot directly control them. In particular, Data packets can only be controlled indirectly through the Interest sending rate adjustment (Chen et al., 2016a). NDN also allows content to be retrieved from multiple (different) paths (multipath) and more than one different source (multisource).

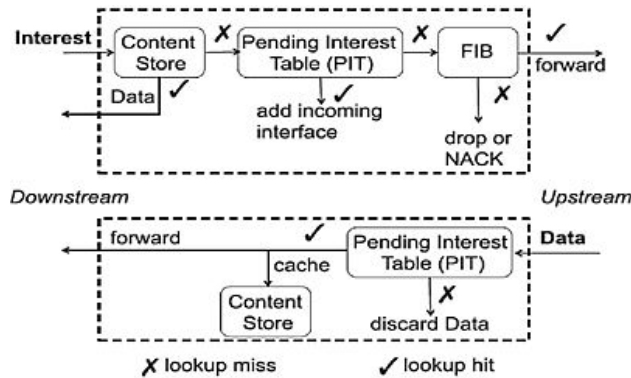
Router Architecture for NDN-Based MANETs

In order to perform the Interest and Data packet forwarding functions, each node maintains three building blocks and one forwarding policy (Figure 2).

Nodes send and receive packets through so-called *faces* which provide communication interfaces to other nodes. Each node makes forwarding decisions using three internal tables: (1) a Content Store (CS) table, (2) a Forwarding Information Base (FIB), (3) a Pending Interest Table (PIT):

- **Content Store (CS):** This is a temporary cache of Data packets that the router has received. A Data packet is cached to satisfy future Interests. The replacement strategy is Least Recently Used (LRU) but the former is determined by the router and may differ. In the transaction model of NDN, in-network caching affects the performance of congestion control. Azgin et al. (2014)

Figure 2. Interest and Data processing in an NDN node (Yi et al., 2012)

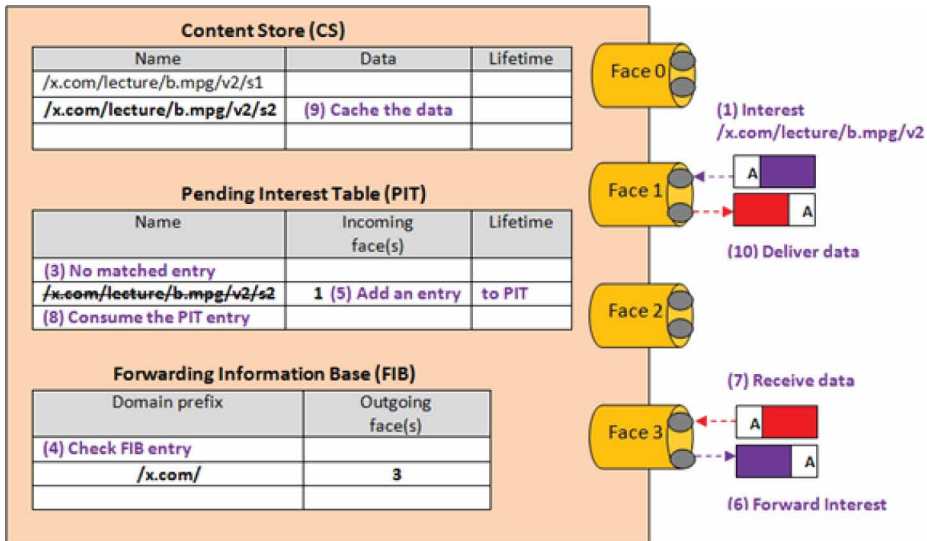


considered the issue of host mobility and proved that finding the CS can introduce significant latency to the system, making information-centric delivery a difficult choice, especially for time-sensitive applications (e.g., voice applications).

- **Forwarding Information Base (FIB):** This table is used to forward Interest packets toward potential content holder(s). FIB is a routing table that maps name components to interfaces. FIB contains the identifiers of the content and determines the outgoing face where the Interest message should be forwarded. FIB itself is populated by a name-prefix-based routing protocol and can have multiple output faces for each prefix. FIB is similar to a classical IP FIB, except for the possibility to have a list of faces for each content name entry. Thus, Interest packets can be forwarded towards many potential sources of the required data.
- **Pending Interest Table (PIT):** PIT stores all the Interests that a router has forwarded but not satisfied yet. Each PIT entry records the data name carried on the network, together with its incoming and outgoing face(s). PIT keeps track of all previously forwarded Interest packets and saves information about the arrival faces. So, it allows the establishment of a backward path to the node that requested the data. Thus, backward Data packets can be delivered to the right requesters.

The *Forwarding Strategy Module (FSM)* operates as follows: when an Interest packet arrives in a node, the node first checks the CS for matching data. The CS is responsible for discovering whether the data item is already available or not. If it is, the node generates a Data packet and sends it back to the requesting user. The router returns the Data packet on the interface from which the Interest came. Otherwise, the router looks up the name of the data item in its PIT. The PIT is consulted to retrieve a Data packet if others' Interest packets requiring the same content have been already forwarded toward potential sources of the required data. In this case (i.e., a matching PIT entry exists), the Interest's arrival face is added to the PIT entry. Otherwise, the FIB is examined to search a matching entry, indicating the list of interfaces that the Interest has to be forwarded through and takes into account the router's adaptive forwarding strategy. In the end, if there is no FIB entry, the Interest is discarded. If a router receives Interests for the same name of the data item from multiple downstream nodes, it forwards only the first one upstream toward the data producer(s). The FSM contains a series of policies and rules about forwarding packets. It performs routing operations only for Interest packets. Data packets, however, just follow the reverse path towards requesting user, allowing every intermediate node to cache the forwarded content. The FSM may decide to drop an Interest packet in certain situations, e.g., if all upstream links are congested or the Interest is suspected to be part of a Denial of Service (DoS) attack. For each Interest packet, the FSM retrieves the longest-prefix matched entry from the FIB and chooses at what time and where to forward the Interest. Figure 3 shows a forwarding model that retrieves video lectures in NDN.

Figure 3. A forwarding model in NDN for distributing video lectures (Kanellopoulos et al., 2020)



In NDN-based MANETs, each node has a fourth table:

- **The Node Status (NS) table:** NS stores special information concerning the node status such as location, battery status, or space available in the CS but also information from its FIB. The information on the NS table is time-dependent and after a while, it is aged out. Fresh information about the node status is requested via a broadcast when an entry is found to have exceeded a configurable time limit used to define 'freshness'. An entry that has exceeded the freshness threshold (but is not considered to be expired) can still be used by the FSM but a request for new statuses will still be triggered. The status information is utilized to make forwarding decisions.

NDN is suitable for MANETs for two reasons (Perez Aruni, 2019):

- **Name resolution and dynamic routing:** IP networks use IP addresses for routing data. Before receiving any desired data, the location (hostname) of these data must be known. In location-based networking, a dedicated link for the path between the consumer and provider node must be established before any data transfer. Once the dedicated link session is established, the Data packet can be sent to the destination node. On the contrary, NDN does not require point-to-point routing information because data are searched and retrieved based on the identity of the data itself (Liu et al., 2019a). This NDN feature renders the routing function more suitable for MANETs.
- **Content caching and traffic optimization:** Content in NDN can be obtained from more than one host. Also, content is not necessarily retrieved from the original source as the content is not uniquely tied to the host. Separation of content and host allows content to be stored in CS. CS allows data to be acquired locally thus increasing the availability of the data itself and reduces the duration required to perform content delivery. NDN can secure the content by naming the data through a security-enhanced method. This method allows trust in data to be separated from trust between hosts and servers, which can potentially enable content caching on the network side to optimize traffic. In conclusion, security is placed on the data itself instead of on the host of the data or even the container of the content. Content is secured by itself and can be cached anyway on the network side to optimize traffic (Zhang et al., 2013). Security features are part of

NDN and enable MANET implementations to get rid of complex security solutions (Liu et al., 2017). Moreover, existing caching strategies applied in NDN can be enhanced to increase network performance. To this end, Lai et al. (2019) derived the Content Popularity and Distance-based Interval (CPDI) caching strategy for NDN-based MANETs, to improve network performance. The CPDI caching strategy can introduce considerable improvements on the average cache hit ratio, the average number of cached Data packets, and the average energy consumption while only slightly degrading the average download delay.

HOW TO CLASSIFY CONGESTION CONTROL PROTOCOLS IN NDN

Congestion control protocols in NDN can be separated into three categories (Kato et al., 2019): (1) receiver-driven; (2) hop-by-hop; (3) hybrid congestion control (viz., a combination of the first two approaches). There are the following criteria for categorization:

- **Which node performs congestion control?** If the consumer node performs congestion control, we have receiver-driven congestion control. If each node performs congestion control, we have hop-by-hop congestion control.
- **Which traffic shaping method is used for congestion control?** (i.e., rate-based or window-based).
- **How is local congestion detection conducted?** It can be implemented by packet loss or timeout or congestion signal using Explicit Congestion Notification (ECN), congestion mark, or negative acknowledgment (NACK).
- **How is the decision for traffic rate or window size made?** This can be achieved by searching the maximum value (threshold), or another mechanism (non-deterministic) or getting the maximum value of traffic rate/'window size' through a congestion signal.

Local Congestion Notification

If a node detects that congestion has occurred at upstream neighbor nodes, the congestion notification mechanism triggers a decrease in traffic rate according to a new threshold. This leads to a reduction of dropped packets in the congested node. This situation also reduces the retransmission of dropped packets and avoids energy wastage. There are three forms of congestion signal (i.e., packet loss, timeout, and congestion mark or NACK) that are used for congestion notification:

- **ECN (Explicit Congestion Notification):** The implicit local congestion detection cannot differentiate between network congestion derived from another next-hop content path and the ones that come from other different content sources. On the contrary, ECN allows network congestion to be accurately known even if it is in a multi-path and multi-source environment such as NDN (Ren et al., 2016b). ECN achieves efficient congestion avoidance and congestion reduction whenever congestion occurs on different content paths and at different content sources. Additionally, it prevents packet drops from occurring if congestion occurs.
- **Piggybacked congestion mark:** This notification method (Schneider et al., 2016; Ye et al., 2017) allows a Data packet to notify downstream neighbor nodes (and a consumer node) if network congestion has occurred. This method adds a special packet header in each Data packet to store information related to congestion control. Such information is congestion window size, a threshold of traffic rate, traffic rate size, suggested traffic rate size based on current available local link bandwidth, etc. This information is sent to neighboring nodes as a reference point for congestion avoidance and/or congestion reduction. In cases of severe network congestion, the Data packet with the congestion mark will probably fail to reach its destination. For this reason, the congestion NACK method is applied.

- **Congestion NACK:** Negative Acknowledgments (NACKs) can notify consumers about cases such as forwarding failures or requests for incorrect or unavailable information. Congestion NACK sends a NACK to the downstream neighbor (or consumer) node when network congestion is detected. Additional important information such as estimated bandwidth value or suggested Interest sending rate to the downstream (or consumer) node is not incorporated in the header of Data packets. In congestion NACK, each Data packet has a very small size and thus has a large probability of reaching directly to the downstream neighbor (or consumer) node despite the problems that may occur. However, the use of congestion NACK tends to lead to the under-utilization of bandwidth usage due to the Interest drop rates which exceed its supposed value. Additionally, congestion NACK raises security issues (Compagno et al., 2015). For example, it facilitates DoS attacks. An option to solve this problem is just to permit Interests time out (expired) if content for them cannot be found. This potentially reduces the level of network traffic.

‘Buffer overflow’ is a local congestion detection method used in BCON (Agarwal & Tahiliani, 2016). BCON is a congestion avoidance protocol for NDN that balances the trade-off between link utilization and data drop rate by leveraging the benefits of Active Queue Management (AQM) mechanisms. Using BCON, Agarwal and Tahiliani (2016) implemented AQM mechanisms in NDN and proved the effectiveness of BCON by performing simulations using ndnSIM. ndnSIM is an open-source simulator used for the performance evaluation of NDN-based systems (Mastorakis et al., 2017).

Rate-Based Traffic Shaping vs. Window-Based Traffic Shaping

Rate-based traffic shaping regulates the number of Interest packets that are going to be sent based on the current estimations of the available local link bandwidth. Bandwidth estimations can be performed using the Leaky Bucket algorithm, the Token Bucket algorithm (Ndikumana et al. 2017), characterizing Interest aggregation (Dabirmoghaddam et al., 2016) and an average occupancy of the PIT (Abu et al., 2016). The congestion control mechanism (Ndikumana et al., 2017) for NDN prevents congestion by monitoring buffer size. Upon reaching the *buffer threshold*, the node notifies its downstream node. On receiving the notification, the downstream node adjusts the traffic rate by allocating new incoming Interests to other face(s). However, when the downstream node fails to reduce the traffic rate, the same procedure continues until the consumer node reduces the sending rate. The advantage of rate-based traffic shaping is that the number of Interest packets is adaptable according to the current status of the available local link bandwidth. However, the bandwidth estimation must be done accurately to avoid the occurrences of two associated anomalies (Kato et al., 2019):

- The first anomaly is the occurrences of network congestion as the number of Data packets received exceeds the actual local bandwidth capacity.
- The second anomaly is that under-utilized network bandwidth causes a goodput value for any one transaction to be much lower.

Rate-based traffic shaping can be used either by receiver-driven or hop-by-hop congestion control as the current Interest sending rate is not dependent on global values (e.g., window size). Examples of congestion control protocols for NDN that adopt rate-based traffic shaping are:

- ECN for NDN (Ren et al., 2016b);
- Congestion control in Stateful Forwarding (Yi et al., 2013);
- HoBHIS (Rozhnova & Fdida, 2014);
- The improved Hop-by-hop Interest Shaper (HIS) (Wang et al., 2013).

The congestion ‘window size’ is determined in terms of the number of Data packets that can be accepted. Window-based traffic shaping adjusts the number of Interest packets sent based on the current ‘window size’. For example, the Additive-Increase/Multiplicative-Decrease (AIMD) feedback congestion control algorithm combines the linear growth of the congestion window with an exponential reduction when congestion occurs. If the retransmission timeout (RTO) elapses without an ACK, severe congestion is concluded. Then, during the first phase of a connection and after a timeout, the ‘slow start’ mechanism is employed that allows for a faster convergence to the correct window size. While ‘slow-start’ is active, the window size is not increased by one segment size for every round-trip-time (RTT), but instead for every received ACK. Window-based traffic shaping has the following drawback. The Interest packet is sent exactly at the amount already set and at the same time. Before the window size is increased, the current Interest packet sent must first receive an ACK in the form of a Data packet required by the particular Interest packet. For example, the current ‘window size’ allows only three Interest packets to be sent and given that each of the three Interest packets has not yet received its respective Data packet, a new Interest packet cannot be sent and, at the same time, the window size will not be increased. As a result, the network bandwidth will not be fully utilized causing energy consumption to occur on bandwidth usage. Additionally, in window-based traffic shaping, the decrement of window size is performed only when network congestion occurs. If local congestion detection is less than accurate and efficient, such decrement also increases the rate of network congestion. Three congestion control protocols for NDN that adopt a window-based traffic shaping method are:

- The Interest Control Protocol (ICP) (Carofiglio et al., 2012a);
- The Information-Centric Transport Protocol (ICTP) (Salsano et al., 2012);
- The congestion control scheme (Fu et al., 2012).

Adaptive Forwarding in Multipath Content Routing

Multipoint relay (MPR) is a neighbor knowledge broadcast protocol that can reduce redundant broadcasting, thus efficiently delivering broadcast packets in both sparse and dense MANETs. In multipath content routing, load distribution is a proactive traffic splitting method that increases the availability of the bandwidth by permitting the use of more than one content path at each given time (Mallapur et al., 2017). Also, load distribution increases energy conservation at each node. NDN already has a built in loop-free multipath content routing feature. Thus, the proactive traffic splitting method has been applied for NDN-based MANETs in many projects (Mahdian et al. 2016; Xin et al., 2016; Bouacherine et al., 2016a; Bouacherine et al., 2016b; Ye et al., 2017). There are three different scenarios where load distribution can be performed in MANETs, namely:

- Duplicating network traffic sent to each different content path.
- Splitting network traffic and forwarding it through different content paths.
- Interest packets for different types of content using different content paths (Udugama et al., 2014).

The adaptive forwarding method (Yi et al., 2012) is generally applied in NDN-based MANETs. According to this method, the traffic of the Interest packet is sent to a single route called ‘*the best content path*’. When this path encounters congestion, the Interest traffic will be forwarded to an alternate content path. However, when the consumer node retransmits the Interest packet before the timeout period, the Interest packet will not be sent using the previous content path (i.e., ‘*the best content path*’), when one of the following two events occurs:

1. The cost value (or ranking) of the content path cannot be found at each alternate path.
2. The cost value (or ranking) at each alternate path is identical.

Adaptive forwarding mainly supports fault tolerance by using a retransmission method for Interest packets. However, it fails to receive the Data packet due to link failure by using an alternate content path. The use of multipath content routing must be optimized to satisfy not only fault tolerance but also the available network load and energy balance requirements. Amadeo et al. (2015) analyzed two classes of forwarding strategies for NDN-based MANETs:

- A minimalist, ‘provider-blind’ forwarding strategy, only aimed at keeping packet redundancy on the broadcast wireless medium under control, without any knowledge about the neighborhood and the identity of the content sources; and
- A ‘provider-aware’ strategy that leverages soft state information about the content sources, piggybacked in Interest and Data packets and locally kept by nodes, to facilitate content retrieval.

The Location-aware On-demand Multipath Caching and Forwarding (LOMCF) (Rehman and Kim, 2017) is another forwarding protocol for NDN-based MANETs. The LOMCF protocol performs better compared with the other recently proposed protocols in terms of content retrieval time, Interest retransmissions, and the total number of Interest packets injected, as well as discarded, in the network. In an NDN-based MANET, if a node has limited residual energy, after sending a few packets, it will die soon. All of its pending request entries are also destroyed, which further exacerbates the communication process. To cope with this problem, Rehman et al. (2017) proposed the On-demand Energy-based Forwarding Strategy (OEFS) protocol, which takes the residual energies of the nodes into account during the entire communication process. OEFS outperforms the existing forwarding protocols in terms of content download time, Interest retransmissions, the total number of Interest propagation, and data redundancy in the network.

Receiver-Driven Congestion Control Solutions for NDN

Receiver nodes can perform Interest shaping for congestion avoidance. Other intermediate nodes can still perform congestion detection, while notifications can be sent to the receiver node to trigger a congestion avoidance action at the receiver node. For example, in such an action, a receiver node can send the current Interest traffic to alternate paths or can decrease the Interest sending rate to avoid congestion. Receiver-driven congestion control is easy to implement as congestion control is only performed by consumer nodes. However, in a multi-source scenario, this approach fails (Ren et al., 2016a). In a multi-source scenario, a consumer node cannot distinguish data traffic from different content providers with the same content name. If the desired content can be obtained in more than one content path, the bandwidth differences of the different content paths must be estimated. Receiver-driven congestion control fails to do this, as it ignores the bandwidth differences for different content paths. Therefore, it results in inappropriate bandwidth estimation of upstream links and causes inefficient Interest shaping. Receiver-driven congestion control regularly uses the explicit congestion control method to overcome the weaknesses of multipath and multisource. In this method, each intermediate node sends information about each of its estimated bandwidths. Based on the information provided, the consumer node will perform Interest rate adjustment. Explicit congestion control is performed using either the NACK or piggybacked method. For example, the Practical Congestion cONtrol (PCON) protocol (Schneider et al., 2016) uses the piggybacked method.

Table 1 compares receiver-driven congestion control protocols for NDN.

Hop-by-Hop Congestion Control Solutions for NDN

Hop-by-hop congestion control is optimal in MANETs because each node in the routing path can react faster on the congestion status to prevent negative effects that will result in network congestion (Chen et al., 2016b). Hop-by-hop congestion control for NDN is not only performed by the receiver node but also by intermediate (relay) nodes. This method allows congestion avoidance action to be performed directly by intermediate nodes without the need to wait for congestion avoidance actions

Table 1. Receiver-driven congestion control protocols for NDN

Congestion Control Scheme	Congestion Control Criteria				
	Congestion Signal	Local Congestion Detection	Traffic Shaping	Window/Rate Size Setting	Multi-source support
ICP (Carofiglio et al., 2012a)	None	RTO Timeout	Window-based	None	No
ICTP (Salsano et al., 2012)	None	RTO Timeout	Window-based	None	No
CCTCP (Content-Centric TCP) (Saino et al., 2013)	None	RTO Timeout for Multi-source	Window-based	None	No
HR-ICP (Hop-by-hop and Receiver-driven Interest Control Protocol) (Carofiglio et al., 2012b)	None	Intermediate node: compare interest rate and its associated data rate Consumer node: RTO Timeout	Window-based	Intermediate node: According to a fair rate of each flow; Consumer node: AIMD	No
- CHoPCoP (Chunkswitched Hop Pull Control Protocol) - pCHoPCoP (Parallel CHoPCoP) (Zhang et al., 2014a)	REM (Random Early Marking)	Intermediate node: Detect outgoing Data queue length and notify receiver by REM	Window-based	Intermediate node: If (queue length > Threshold), then delay Interest forwarding; Consumer node: AIMD	Yes
ECP (Explicit Control Protocol) (Ren et al., 2015)	ECN	Length of interest queue	Window-based	None	No
ECN (Explicit Congestion Notification) for NDN (Ren et al., 2016b)	ECN	Congestion notification	Rate-based	Rate notification	No
ConTug (Arianfar et al., 2010)	None	RTO Timeout	Window-based	AIMD-like and linearly decrease in weak congestion	Yes
PCON (Schneider et al., 2016)	Congestion Mark	ColDel AQM	Window-based	AIMD	No

(Mejri et al., 2017). Each hop performs its own separate congestion control adapted to the current state of each hop on each content path. This renders hop-by-hop congestion control for NDN more suitable for multipath and multisource scenarios as each content path and each content source has its own Interest rate according to the current state. If network congestion occurs in a node, its neighbor nodes perform congestion avoidance directly without waiting for the consumer node to do so. Changes of content paths or the decrease in Interest rate to avoid negative effects can be performed immediately at each downstream neighbor node without waiting for the consumer node to decide the next action.

Famous hop-by-hop congestion control protocols for NDN are the Hop-by-hop Interest Shaping mechanism (HoBHIS) (Rozhnova & Fdida, 2014), the improved hop-by-hop Interest shaper (Wang et al., 2013), Popularity-based Congestion Control (Park et al., 2014), RCP-based Congestion Control Protocol (Lei et al., 2015), Multi-path Flow Control (MFC) (Li et al., 2015), and Rate-Based Congestion Control (Kato & Bandai, 2018). All these congestion control protocols use a rate-based traffic shaping method:

- **Hop-by-hop Window-based Congestion Control (HWCC) (Kato et al., 2019):** HWCC is the only protocol that applies a hop by hop window-based traffic shaping. HWCC allows each local hop to have its own window size according to the condition of the local link bandwidth. Each node performs either Interest shaping or reactive local congestion detection to detect congestion at their respective local links without relying on consumer nodes.
- **Stateful Forwarding Mechanism (SFM) (Yi et al., 2013):** SFM facilitates the integration of congestion control with a routing mechanism, a connectionless transaction that allows easy hop-by-hop congestion control, native support for multipath routing, and in-network caching using

the CS to improve the availability of the required content. NDN supports hop-by-hop congestion control since NDN forwarding is stateful and transparent.

- **Hop-by-hop Interest Shaping (HoBHIS) (Rozhnova & Fdida, 2014):** HoBHIS relies on traffic shaping without any additional mechanism to detect network congestion such as MIRCC.
- **Multipath-aware ICN Rate-based congestion control (MIRCC):** A challenge is to ensure full network utilization while maintaining fairness among the competing flows regardless of the number of paths. MIRCC (Mahdian et al., 2016) tackles the problem of coupling multipath routing/forwarding with objectives such as fairness, congestion control, and network utilization. MIRCC is a rate-based multipath-aware congestion control protocol for NDN inspired by the Rate Control Protocol (RCP). However, the MIRCC algorithm has much better convergence time and less overshoot and oscillation than classic RCP.
- **Remote Adaptive Active Queue Management (RAAQM) (Carofiglio et al., 2013):** RAAQM adds support to the multi-source scenarios by creating different congestion window sizes for each different content path because every content path has different local link bandwidth at any one time.
- **Best Effort Link Reliability Protocol (BELRP) (Vusirikala et al., 2016):** BELRP detects network congestion using the link loss detection method. However, it cannot differentiate link loss due to network congestion from link loss caused by other factors such as bit errors, link outages, and hardware failure. As a consequence, BELRP performs the same link loss recovery approach, that is, through the fast retransmission method towards LpPacket that failed to receive ACK until it reached RTO. Therefore, the use of a fast retransmission method solely for congestion avoidance and congestion recovery is impractical for use in NDN-based MANETs.

Table 2 compares the main hop-by-hop congestion control schemes for NDN.

CONGESTION CONTROL SOLUTIONS FOR NDN-BASED MANETS

Each node uses a broadcast algorithm to forward a packet (Ruiz & Bouvry, 2015). The simplest broadcast algorithm (known as *flooding*) consists of retransmitting every received packet. Flooding is inappropriate as it not only leads to network congestion but also drains the batteries of mobile devices. Flooding also generates the “*broadcast storm*” problem, i.e., the higher the network density, the higher the number of collisions, packet losses, the contention of the shared medium, network traffic, and network resources.

Table 2. Hop-by-hop congestion control schemes for NDN

Congestion Control Scheme	Congestion Control Criteria				
	Congestion Signal	Local Congestion Detection	Traffic Shaping	Window/Rate Size Setting	Multi-source support
HWCC (Kato et al., 2019)	None	Length of interest queue	Window-based	Rate notification	No
SFM (Yi et al., 2013)	ECN	Congestion notification	Rate-based	None	No
HoBHIS (Rozhnova and Fdida, 2014)	ECN	None	Rate-based	Rate notification	No
MIRCC (Mahdian et al., 2016)	ECN	None	Rate-based	Rate notification	No
RAAQM (Carofiglio et al., 2013)	None	Timeout for each content path using RTT calculation.	Window-based	AIMD	Yes
BELRP (Vusirikala et al., 2016)	Congestion Mark	Link loss detection	None	None	No

Existing congestion control solutions for NDN mainly assume that link capacity is fixed and thus already known. This assumption cannot be true for MANETs (Ahlgren et al., 2018). Until now, a complete congestion control solution for NDN-based MANETs has not been proposed. Almost all works merely focus on specific issues about network congestion. For example, many content routing solutions for NDN-based MANETs use wireless broadcast algorithms such as CHANET (Amadeo & Molinaro, 2011), E-CHANET (Amadeo et al., 2013), Best Route Error Broadcast (BREB) (Han et al., 2014) and CSAR (Kuang & Yu, 2015). Therefore, these works focus mainly on broadcast control solutions to relieve broadcast storms rather than on real congestion control solutions to prevent network congestion. Hereafter, we discuss only those works that propose real congestion control solutions for NDN-based MANETs.

E-CHANET

E-CHANET (Amadeo et al., 2013) uses a proactive congestion avoidance method by performing Interest sending rate adjustment on consumer nodes, based on two parameters:

- *Sustainable Transmission Rate* (STR) of Data packets that is measured in congested nodes. STR information is sent from the congested node to the consumer node via the packet's header Rate Info data. STR represents the impact of the medium access delay.
- *Inter Data Gap* (IDG) is measured within the consumer node itself. IDG represents wireless channel status.

The combination of STR and IDG represents the estimated current wireless link bandwidth. E-CHANET uses three Interest shaping modes: init mode, slow-start mode, and normal mode. In init mode, only the IDG value is obtained and the Interest rate does not change based on the estimated bandwidth value of IDG. When the initial STR value is obtained from the consumer node itself, the slow-start mode will be used. At this point, the Interest rate will then be raised exponentially until it reaches the maximum limit of Interest sending rate, which is obtained based on the formula that uses IDG and STR values. However, if the consumer node receives an STR value from the congested node, the normal mode will then be used. In this case, the Interest sending rate changes accordingly, following the formula that uses the IDG and STR value of the congested node.

SIRC

Amadeo et al. (2014b) improved the congestion control mechanism of E-CHANET by deploying a new scheme called 'Self-regulating Interest Rate Control' (SIRC). SIRC is responsible for Interest transmission and a re-transmission schedule without relying on RTO as practised in AIMD. In SIRC, the Interest sending rate is adjusted based on IDG without relying on the STR value. On the contrary, consumer nodes perform self-regulated calculations based on data inter-arrival time to identify Interest rate transmissions appropriate for Interest transmission purposes. SIRC only has two Interest rate schemes: init mode and normal mode. Init mode is the Interest rate broadcast in the starting phase when there is no data or very little packet data received to determine the appropriate Interest sending rate. Similar methods used in slow-start and AIMD are used in this phase to determine the current Interest rate. The normal mode refers to the Interest sending rate determined based on IDG and is measured by using the propagated algorithm for SIRC. This phase uses IDG to assume current available network bandwidth based on a calculation made against IDG.

The congestion control methods used in E-CHANET and SIRC have two weaknesses:

- Both methods are receiver-driven. This feature renders them impractical for NDN-based MANETs.
- Both methods are entirely dependent on traffic shaping and retransmission methods for congestion avoidance. Congestion is only detected indirectly through the self-regulated calculation of the

inter-arrival time method, which is less accurate and efficient in identifying the occurrence of network congestion within a dynamic NDN-based MANET environment.

CHoPCoP

CHoPCoP (Chunk-switched Hop Pull Control Protocol) (Zhang et al., 2014a) is the only congestion control protocol that works in wired networks and MANETs. CHoPCoP consists of three components:

- *Explicit congestion signalling* that is used to satisfy the multipath and multisource requirements. This signalling is implemented using the Random Early Marking (REM) method that enables traffic shaping within the multisource and multipath environment. REM uses the probability of data rate through the data queue in the forwarder. The sampling method is used to measure the data rate to be selected.
- *Fair Share Interest Shaping (FISP) mechanism*. FISP achieves the fairness of network bandwidth utilization. FISP ensures the fairness of bandwidth utilization through the lightweight fair scheduling method for each different queue through the same intermediate node. FISP allows each of the different flows of network traffic within the shared network bandwidth to achieve the same network bandwidth capacity through the flow scheduling method based on a delay-based probability technique.
- *AIMD-based receiver Interest control*: It is a receiver-driven traffic shaping mechanism that controls the transmission rate of Interest packets as a proactive action of network bandwidth utilization efficiency. The consumer node controls the Interest rate transmission by using the AIMD mechanism. AIMD combines the linear growth of the congestion window with an exponential reduction when congestion occurs. Interest control consists of two phases: (1) the 'slow start' phase; and (2) the 'congestion avoidance phase'. The 'slow start' phase starts when the consumer node takes the first Interest packet and the window size increases linearly up to the threshold value or when network congestion is detected. Subsequently, the control of Interest packets takes place in the congestion avoidance phase, where the window size will increase at a lower rate or decrease if congestion is detected. Local congestion is detected using the timeout method and if congestion occurs on another node, the congestion signal is used.

pCHoPCoP

Parallel CHoPCoP (pCHoPCoP) (Zhang et al., 2015) is an extension of CHoPCoP. Through different network interfaces, pCHoPCoP allows the retrieval of data in a multisource context in parallel. In the consumer node, many CHoPCoP controllers run, and each CHoPCoP controller is connected to each different interface network. Inside the consumer node, the pCHoPCoP engine centrally controls the cooperation of each different CHoPCoP controller. When the NDN application sends a request to the pCHoPCoP engine, the pCHoPCoP controller distributes the Interest packet to each different CHoPCoP controller, which then receives its respective packet data. The consolidation of Data packets is performed by the pCHoPCoP engine before they are sent to the NDN application.

CHoPCoP and pCHoPCoP constitute incomplete congestion control solutions for NDN-based MANETs because they use a receiver-driven congestion control method. Also, the consumer node must have inputs to network traffic. In order to detect local network congestion, intermediate (relay) nodes determine the length of the '*Outgoing Data queue*' and notify the consumer node by using REM for further action. If this queue length is larger than a *threshold*, then the forwarding of Interest packets is delayed. Zhang et al. (2015) declare that network congestion is indirectly detected locally through an introduced probability sampling method used to measure the data rate. Zhang et al. (2014a) also stated that their probability sampling method is more accurate than the use of RTT for data rate estimation. However, it is not clear how the proposed probability method (based on measuring data rate) determines the proper Interest rate transfer before the process of Interest forwarding starts.

Consequently, we conclude that CHoPCoP has no dedicated congestion detection for NDN-based MANETs.

Adaptive Congestion Control Protocol (ACCP)

The ACCP protocol (Liu et al., 2019b) differs from other protocols that use the congestion NACK method. The extended (modified) NACK mechanism of ACCP allows the information concerning the congestion level to be more informative. The extended NACK packet includes an additional congestion status field to hold one of four congestion levels (idle link, light busy link, heavy busy link, congestion link). This extra information is sent as a negative feedback when congestion occurs. ACCP is divided into two phases to control congestion before affecting network performance:

- In the first phase, the time series prediction model is employed. This model is based on deep learning to predict the source of congestion for each node.
- In the second phase, the level of network congestion is estimated by the average queue length based on the outcomes of the first phase in each router and explicitly returns it back to the receiver. Next, the receiver adjusts the sending rate of Interest packets to realize congestion control.

ACCP has a better performance than ICP and CHoPCoP in terms of high utilization and minimal packet drop in a multi-source/multi-path environment.

CROSS-LAYER CONGESTION CONTROL FOR NDN-BASED MANETS

Some cross-layer methods (Li et al., 2016; Li et al., 2017a; Li et al., 2017b) optimize the integration between the congestion control module and the other modules (e.g., forwarding strategy, link scheduler, and power control) in the NDN forwarder. However, an effective design of cross-layer congestion control for NDN-based MANETs has not been put forward yet. In particular, researchers focus mainly on cross-layer based integration methods that solve partial integration optimization problems.

The NDNUM (Named-Data Network Utility Maximization) framework (Li et al., 2016) aspires to generate communication methods in an NDN-based MANET that will maximize the use of available network resources with minimal transmission power consumption. These methods will reduce interference and increase the energy efficiency of MANET. In NDNUM, the proposed cross-layer method combines congestion control, forwarding strategy, and power control. Network congestion is solved using a methodology that decides how transactions can be optimally carried out within a MANET. Also, congestion control uses exclusively traffic shaping and a receiver-driven approach where the consumer node determines the Interest rate based on the current Lagrangian multiplier value. This current value aims to reduce the overhead for congestion control relative to the global window size usage implemented in previous work related to congestion control for NDN. Based on network congestion as input (a bounded limit), the Lagrangian method of multiplier optimization determines the optimum communication method.

Li et al. (2017a) proposed the integration of congestion control, forwarding strategy, and link scheduling using a more advanced cross-layer method. They also used the Lagrangian method of multiplier optimization. They focused on improving network throughput and efficiency of resource utilization through an Interest setting and an efficient data sending rate, the efficient selection of Interest and traffic data that will pass through the active link, and the active duration of the link. Li et al. (2017b) put forward a similar cross-layer method for congestion control that integrates both a forwarding strategy and other mechanisms to create a jointly optimized solution. However, they applied the Lyapunov optimization technique that uses a Lyapunov function to optimally control the stability of an NDN-based MANET. A Lyapunov function can stabilize all network queues while optimizing some performance objectives (e.g., maximizing the average throughput).

Table 3 summarizes the main congestion control protocols.

SHORTCOMINGS AND OPEN CHALLENGES

Congestion control protocols for NDN-based MANETs try to avoid transmission buffer overflow at NDN routers, perform early congestion detection, and protect from misbehaving receivers. However, these protocols have two shortcomings: (1) these protocols assume that link capacity is fixed and thus already known. This assumption cannot be true for MANETs. Therefore, protocol developers must consider the variability of link capacity when they implement congestion control. Such a consideration presupposes a holistic, adaptive forwarding strategy that will take into account various QoS metrics (e.g., bandwidth, delay, loss-rate, reliability, energy efficiency, etc.); (2) Finding the CS can introduce significant latency to the system, thus making information-centric delivery a difficult choice for time-sensitive applications. Decreasing this latency requires intelligent adaptive forwarding strategies.

Challenges

The Forwarding Strategy Module (FSM) allows for dynamically selecting network interfaces taking into account network conditions (e.g., delay) to forward Interest packets toward a provider. However, a challenge is to define proper criteria for selecting the best possible paths to forward Interest messages

Table 3. A comparison of the main congestion control schemes for NDN-based MANETs

Congestion Control Scheme	Features	Comments
E-CHANET	<ul style="list-style-type: none"> The Interest sending rate adjustment on consumer nodes is based on STR and IDG. It uses three different Interest shaping modes: init mode, slow-start mode, and normal mode. 	<ul style="list-style-type: none"> The congestion control method used is receiver-driven and is entirely dependent on traffic shaping and retransmission methods for congestion avoidance.
SIRC	<ul style="list-style-type: none"> The Interest sending rate is adjusted based on IDG without relying on the STR value. It has two Interest rate schemes: init mode and normal mode. 	<ul style="list-style-type: none"> The method used is receiver-driven. This feature renders SIRC (and E-CHANET) impractical for NDN-based MANETs.
CHoPCoP	<ul style="list-style-type: none"> CHoPCoP consists of three components: (1)Explicit congestion signalling; (2) FISP mechanism; (3) AIMD-based receiver Interest control. 	<ul style="list-style-type: none"> Explicit congestion signalling is implemented through the REM method.
Parallel CHoPCoP	<ul style="list-style-type: none"> It allows the retrieval of data in a multisource context simultaneously. 	<ul style="list-style-type: none"> CHoPCoP has no dedicated congestion detection for NDN-based MANETs.
ACCP	<ul style="list-style-type: none"> ACCP uses an extended NACK mechanism that informs the consumer node about four congestion levels. 	<ul style="list-style-type: none"> ACCP has a better performance than ICP and CHoPCoP in terms of high utilization and minimal packet drop in a multi-source/multi-path environment.
NDNUM	<ul style="list-style-type: none"> The proposed cross-layer method provides a solution combining congestion control, forwarding strategy, and power control. 	<ul style="list-style-type: none"> The consumer node determines the Interest rate based on the current Lagrangian multiplier value, which aims to reduce the overhead for congestion control relative to the global window size usage.
Li et al. (2017a)	<ul style="list-style-type: none"> It is a cross-layer scheme that integrates congestion control, forwarding strategy, and link scheduling. It uses the Lagrangian method of multiplier optimization. 	<ul style="list-style-type: none"> It improves throughput and efficiency of resource utilization through an Interest setting and an efficient data sending rate, the efficient selection of Interest and traffic data that will pass through the active link, and the active duration of the link.

because different QoS parameters and conditions conflict with one another when choosing the best interfaces. For example, if there are two potential paths for forwarding Interest packets, these paths often have dissimilar QoS properties. Selecting the path having less end-to-end delay in forwarding Interest packets does not guarantee that this path will have less loss-rate or high bandwidth. Existing forwarding strategies do not take into consideration an attacker who tries to inject(input) fake data with the same name as valid data. Therefore, a challenge is to take a holistic, adaptive forwarding approach that will examine jointly reliability and other QoS metrics such as bandwidth, load, and delay. It is important to introduce a reliability metric that will define which path is more stable and reliable for retrieving legitimate data, because such metric can enhance connectivity. To this end, Rezaeifar et al. (2019) only proposed a reliable adaptive forwarding approach that enables reliable message delivery against potential attackers that inject invalid data. The introduced reliability metric defines which path is more stable and reliable for retrieving data. Another challenge is to reduce the transmission delay of Interest packets and improve the transmission reliability because deploying NDN directly in a MANET tends to result in the high transmission delay of Interest packets. To this end, Ma et al. (2020) made full use of the advantages of standard NDN's CS, and added the confirmation response and timeout retransmission mechanism of Interest packets without changing the standard NDN communication mechanism. The proposed mechanism achieves the reliable and efficient transmission of Interest packets on wireless links with a high packet loss-rate. Their mechanism is better than the standard NDN method in reducing transmission delay and improving transmission efficiency. However, further streamlining is required in the structure design related to the Interest packet table and adding congestion control mechanisms in NDN-based MANETs. One more challenge is to implement prototypes of NDN-based MANETs over open-source simulators for experimentation. This will allow protocol developers to perform simulation experiments on congestion control. To this end, Kato et al. (2018) implemented an NDN-based MANET over ndnSIM. They demonstrated how to construct PIT and FIB using the face and the MAC address, and how to allow the content chunk layer to use the MAC address contained in WiFi data frames. They also presented the implementation of the Interest broadcasting method, the revised reactive routing method, and the Optimized Link State Routing Protocol (OLSR)-based NDN method. Perez Aruni (2019) implemented an open-source prototype, called *Java NDN Forwarding Daemon* (JNFD). The source code of JNFD is created in Bitbucket repositories (JNFD, 2019) using the Git version control system (<https://git-scm.com/>) for tracking code changes. An open repository of the source code is provided, as well as a description of the cases of each experiment, and an open repository of the collected experimental data sets, their analysis, and data processing tools. Researchers can reproduce new experiments that will evaluate congestion control protocols by exploiting these tools, input data sets, and the evaluation methodology.

CONCLUSION

This survey article reviewed congestion control protocols for NDN-based MANETs. The majority of these protocols use a proactive congestion avoidance approach via an Interest-shaping mechanism. Such a congestion avoidance approach controls the Interest sending rate to avoid network congestion. When network congestion occurs, only the retransmission of the dropped packets is performed. In NDN-based MANETs, congestion control is often achieved through receiver-driven or hop-by-hop congestion control and by applying rate-based or window-based traffic shaping. The determination of the maximum value (threshold) of rate/window size constitutes a crucial design parameter for congestion control. Congestion control mechanisms must also avoid transmission buffer overflow at NDN routers, perform early congestion detection, and protect from misbehaving receivers. This survey article presented various design issues of congestion control in NDN-based MANET. It mentioned all the recent advances in all types of congestion control. This study can be utilized as a guideline to address some of the unresolved challenges in the field of congestion control for NDN-based MANETs.

REFERENCES

- Abu, A.J., Bensaou, B., & Abdelmoniem, A.M. (2016). *Leveraging the pending interest table occupancy for congestion control in CCN*. IEEE Local Computer Networks (LCN), Dubai, UAE.
- Agarwal, A., & Tahiliani, M. (2016). BCON: Back pressure based congestion avoidance model for named data networks. In *Proceedings of the 2016 IEEE International Conference on Advanced Networks and Telecommunications Systems* (pp.1–5). IEEE. doi:10.1109/ANTS.2016.7947823
- Ahlgren, B., Dannewitz, C., Imbrenda, C., Kutscher, D., & Ohlman, B. (2012). A survey of information-centric networking. *IEEE Communications Magazine*, 50(7), 26–36. doi:10.1109/MCOM.2012.6231276
- Ahlgren, B., Hurtig, P., Abrahamsson, H., Grinnemo, K., & Brunstrom, A. (2018). ICN congestion control for wireless links. In *Proceedings of the 2018 IEEE Wireless Communications and Networking Conference* (pp.1–6). IEEE. doi:10.1109/WCNC.2018.8377396
- Al-Adhaileh, M. H., Muchtar, F., Abdullah, A. H., & Singh, P. K. (2020). The significance of using NDN in MANET. In *Proceedings of ICRIC 2019* (pp.421–437). Springer. doi:10.1007/978-3-030-29407-6_31
- Al-Turjman, F. (2018). Information-centric framework for the Internet of Things (IoT): Traffic modeling & optimization. *Future Generation Computer Systems*, 80, 63–75. doi:10.1016/j.future.2017.08.018
- Amadeo, M., Campolo, C., & Molinaro, A. (2015). Forwarding strategies in named data wireless ad hoc networks: Design and evaluation. *Journal of Network and Computer Applications*, 50, 148–158. doi:10.1016/j.jnca.2014.06.007
- Amadeo, M., Campolo, C., Molinaro, A., & Ruggeri, G. (2014a). Content-centric wireless networking: A survey. *Computer Networks*, 72, 1–13. doi:10.1016/j.comnet.2014.07.003
- Amadeo, M., & Molinaro, A. (2011). CHANET: A content-centric architecture for IEEE 802.11 MANETs. In *Proceedings of the 2011 IEEE International Conference on the Network of the Future* (pp.122–127). doi:10.1109/NOF.2011.6126671
- Amadeo, M., Molinaro, A., Campolo, C., Sifalakis, M., & Tschudin, C. (2014b). Transport layer design for named data wireless networking. In *2014 IEEE Conference on Computer Communications Workshops* (pp.464–469). doi:10.1109/INFCOMW.2014.6849276
- Amadeo, M., Molinaro, A., & Ruggeri, G. (2013). E-CHANET: Routing, forwarding and transport in information-centric multihop wireless networks. *Computer Communications*, 36(7), 792–803. doi:10.1016/j.comcom.2013.01.006
- Arianfar, S., Nikander, P., Eggert, L., & Ott, J. (2010). *ConTug: A receiver-driven transport protocol for content-centric networks* (Vol. 2010). IEEE ICNP.
- Azgin, A., Ravindran, R., & Wang, G. (2014). Mobility study for named data networking in wireless access networks. In *Proceedings of the 2014 IEEE International Conference on Communications* (pp.3252–3257). IEEE. doi:10.1109/ICC.2014.6883822
- Bouacherine, A., Senouci, M. R., & Merabti, B. (2016a). Parallel multi-path forwarding strategy for named data networking. In *Proceedings of the 13th International Joint Conference on e-Business and Telecommunications* (pp.36–46). doi:10.5220/0005964600360046
- Bouacherine, A., Senouci, M. R., & Merabti, B. (2016b). Multipath forwarding in named data networking: Flow, fairness, and context-awareness. In *Proceedings of the International Conference on E-Business and Telecommunications* (pp.23–47). Springer. doi:10.1007/978-3-319-67876-4_2
- Carofiglio, G., Gallo, M., & Muscariello, L. (2012a). ICP: Design and evaluation of an Interest control protocol for content-centric networking. In *Proceedings of the 2012 IEEE INFOCOM Workshops* (pp.304–309). doi:10.1109/INFCOMW.2012.6193510
- Carofiglio, G., Gallo, M., & Muscariello, L. (2012b). Joint hop-by-hop and receiver-driven interest control protocol for content-centric networks. *Computer Communication Review*, 42(4), 491–496. doi:10.1145/2377677.2377772

- Carofiglio, G., Gallo, M., Muscariello, L., & Papali, M. (2013). Multipath congestion control in content-centric networks. In *Proceedings of the 2013 IEEE Conference on Computer Communications Workshops*, (pp.363–368). doi:10.1109/INFCOMW.2013.6970718
- Chen, Q., Xie, R., Yu, F. R., Liu, J., Huang, T., & Liu, Y. (2016a). Transport control strategies in named data networking: A survey. *IEEE Communications Surveys and Tutorials*, 18(3), 2052–2083. doi:10.1109/COMST.2016.2528164
- Chen, W., Guan, Q., Jiang, S., Guan, Q., & Huang, T. (2016b). Joint QoS provisioning and congestion control for multi-hop wireless networks. *EURASIP Journal on Wireless Communications and Networking*, 2016(1), 1–11. doi:10.1186/s13638-016-0519-2
- Compagno, A., Conti, M., Ghali, C., & Tsudik, G. (2015). To NACK or not to NACK? negative acknowledgments in information-centric networking. In *Proceedings of the 24th International Conference on Computer Communication and Networks* (pp.1–10). doi:10.1109/ICCCN.2015.7288477
- Dabirmoghaddam, M., Dehghan, J., & Garcia-Luna-Aceves, J. (2016). Characterizing Interest aggregation in content-centric networks. In *Proceedings of the 2016 IFIP Networking Conference and Workshops* (pp.449–457). doi:10.1109/IFIPNetworking.2016.7497205
- Fu, T., Li, Y., Lin, T., Tan, H., Tang, H., & Ci, S. (2012). An effective congestion control scheme in content-centric networking. In *Proceedings of the 13th IEEE International Conference on Parallel and Distributed Computing, Applications and Technologies* (pp. 245–248). doi:10.1109/PDCAT.2012.43
- Han, H., Wu, M., Hu, Q., & Wang, N. (2014). Best Route, Error Broadcast: A content-centric forwarding protocol for MANETs. In *Proceedings of the IEEE 80th Vehicular Technology Conference* (pp.1–5). doi:10.1109/VTCFall.2014.6965890
- Jaber, G., Kacimi, R., & Gayraud, T. (2017). Data freshness aware content-centric networking in WSNs. In *Proceedings of the 2017 Wireless Days* (pp.238–240). IEEE. doi:10.1109/WD.2017.7918152
- JNFD. (2019). *Source code of JNFD in Bitbucket repositories*. Available at <https://bitbucket.org/percyperezdj/nfdmanet>
- Kanellopoulos, D. (2017). QoS routing for multimedia communication over wireless mobile ad hoc networks: A survey. *International Journal of Multimedia Data Engineering and Management*, 8(1), 42–71. doi:10.4018/IJMDM.2017010103
- Kanellopoulos, D. (2019). Congestion control for MANETs: An overview. *ICT Express*, 5(2), 77–83. doi:10.1016/j.icte.2018.06.001
- Kanellopoulos, D. (2020). Academic video lectures over named data networking. *Information Discovery and Delivery*, 48(4), 165–177. doi:10.1108/IDD-10-2019-0071
- Kanellopoulos, D., & Sharma, V. (2020). Survey on power-aware optimization solutions for MANETs. *Electronics (Basel)*, 9(7), 1129. doi:10.3390/electronics9071129
- Kato, T., & Bandai, M. (2018). Avoiding excessive rate reduction in rate based congestion control for Named Data Networking. *Journal of Information Processing*, 26(0), 29–37. doi:10.2197/ipsjip.26.29
- Kato, T., Bandai, M., & Yamamoto, M. (2019). A congestion control method for Named Data Networking with hop-by-hop window-based approach. *IEICE Transactions on Communications*, 102-B(1), 97–110. doi:10.1587/transcom.2018EBP3045
- Kato, T., Minh, N. Q., Yamamoto, R., & Ohzahata, S. (2018). How to implement NDN MANET over ndnSIM simulator. In *Proceedings of the 4th IEEE International Conference on Computer and Communications*, (pp.451–456). IEEE. doi:10.1109/CompComm.2018.8780792
- Khelifi, H., Luo, S., Nour, B., Moun gla, H., Faheem, Y., Hussain, R., & Ksentini, A. (2020). Named data networking in vehicular ad hoc networks: State-of-the-art and challenges. *IEEE Communications Surveys and Tutorials*, 22(1), 320–351. doi:10.1109/COMST.2019.2894816
- Kim, D., Kim, J. H., Moon, C., Choi, J., & Yeom, I. (2016). Efficient content delivery in mobile ad-hoc networks using CCN. *Ad Hoc Networks*, 36(1), 81–99. doi:10.1016/j.adhoc.2015.06.007

- Kitchenham, B. (2004). *Procedures for performing systematic reviews*. Keele, UK: Keele University. Technical Report TR/SE-0401.
- Kuang, J., & Yu, S. Z. (2015). CSAR: A content-scent based architecture for information-centric mobile ad hoc networks. *Computer Communications*, 71, 84–96. doi:10.1016/j.comcom.2015.09.024
- Lai, J., Li, C., Chen, Z., Sun, Y., & Xiao, H. (2019). A novel content popularity and distance based interval caching strategy for named data mobile ad-hoc network (NDMANET). In *Proceedings of the 2nd IEEE International Conference on Computer and Communication Engineering Technology*, (pp. 259–263). doi:10.1109/CCET48361.2019.8989033
- Lei, K., Hou, C., Li, L., & Xu, K. (2015). A RCP-based congestion control protocol in named data networking. In *Proceedings of the 2015 IEEE International Conference on Cyber-Enabled Distributed Computing and Knowledge Discovery* (pp.538–541). doi:10.1109/CyberC.2015.67
- Li, C., Huang, T., Xie, R., Zhang, H., Liu, J., & Liu, Y. (2015). A novel multi-path traffic control mechanism in named data networking. In *Proceedings of the 22nd IEEE International Conference on Telecommunications (ICT 2015)* (pp.60–66). doi:10.1109/ICT.2015.7124658
- Li, C., Xie, R., Huang, T., & Liu, Y. (2016). Jointly optimal congestion control, forwarding strategy and power control for named-data multihop wireless network. *IEEE Access: Practical Innovations, Open Solutions*, 5, 1013–1026. doi:10.1109/ACCESS.2016.2634525
- Li, C., Xie, R., Huang, T., & Liu, Y. (2017a). Jointly optimized congestion control, forwarding strategy, and link scheduling in a named-data multihop wireless network. *Frontiers of Information Technology & Electronic Engineering*, 18(10), 1573–1590. doi:10.1631/FITEE.16001585
- Li, C., Xie, R., Huang, T., & Liu, Y. (2017b). Cross-layer congestion control in named-data multihop wireless networks. *Ad-Hoc & Sensor Wireless Networks*, 39(1-4), 61–95.
- Liu, H., Azhandeh, K., de Foy, X., & Gazda, R. (2019a). A comparative study of name resolution and routing mechanisms in information-centric networks. *Digital Communications and Networks*, 5(2), 69–75. doi:10.1016/j.dcan.2018.03.005
- Liu, T., Zhang, M., Zhu, J., Zheng, R., Liu, R., & Wu, Q. (2019b). ACCP: Adaptive congestion control protocol in named data networking based on deep learning. *Neural Computing & Applications*, 31(9), 4675–4683. doi:10.1007/s00521-018-3408-2
- Liu, X., Li, Z., Yang, P., & Dong, Y. (2017). Information-centric mobile ad hoc networks and content routing: A survey. *Ad Hoc Networks*, 58, 255–268. doi:10.1016/j.adhoc.2016.04.005
- Ma, M., Gao, F., Li, T., Zhang, Y., & Hao, Y. (2020). Reliable transmission mechanism of interest in named data wireless multi-hop network. In *Proceedings of the 4th IEEE Information Technology, Networking, Electronic and Automation Control Conference*, (Vol. 1, pp.1158–1163). doi:10.1109/ITNEC48623.2020.9085105
- Mahdian, M., Arianfar, S., Gibson, J., & Oran, D. (2016). MIRCC: Multipath-aware ICN rate-based congestion control. In *Proceedings of the 3rd ACM Conference on Information-Centric Networking* (pp.1–10). doi:10.1145/2984356.2984365
- Mallapur, S. V., Patil, S. R., & Agarkhed, J. V. (2017). Load balancing technique for congestion control multipath routing protocol in MANETs. *Wireless Personal Communications*, 92(2), 749–770. doi:10.1007/s11277-016-3575-3
- Mastorakis, S., Afanasyev, A., & Zhang, L. (2017). On the evolution of ndnSIM: An open-source simulator for NDN experimentation. *Computer Communication Review*, 47(3), 19–33. doi:10.1145/3138808.3138812
- Mejri, S., Touati, H., Malouch, N., & Kamoun, F. (2017). Hop-by-hop congestion control for named data networks. In *Proceedings of the IEEE/ACS 14th International Conference on Computer Systems and Applications* (pp.114–119). doi:10.1109/AICCSA.2017.36
- Muchtar, F., Abdullah, A. H., Hassan, S., Khader, A. T., & Zamli, K. Z. (2019). Energy conservation of content routing through wireless broadcast control in NDN based MANET: A review. *Journal of Network and Computer Applications*, 131, 109–132. doi:10.1016/j.jnca.2019.01.004

- Ndikumana, A., Ullah, S., Thar, K., Tran, N. H., Park, B. J., & Hong, C. S. (2017). Novel cooperative and fully-distributed congestion control mechanism for content centric networking. *IEEE Access: Practical Innovations, Open Solutions*, 5, 27691–27706. doi:10.1109/ACCESS.2017.2778339
- Park, H., Jang, H., & Kwon, T. (2014). Popularity-based congestion control in named data networking. In *Proceedings of the 6th International Conference on Ubiquitous and Future Networks* (pp.166–171). IEEE. doi:10.1109/ICUFN.2014.6876774
- Perez Aruni, P. D. (2019). *Applying Named Data Networking in Mobile Ad hoc Networks* (Doctoral dissertation). University of St Andrews.
- Rath, M., Rout, U. P., Pujari, N., Nanda, S. K., & Panda, S. P. (2017). *Congestion control mechanism for real time traffic in mobile adhoc networks. In Lecture Notes in Networks and Systems* (Vol. 5). Springer., doi:10.1007/978-981-10-3226-4_14
- Rehman, R. A., Ahmed, S. H., & Kim, B. S. (2017). OEFS: On-demand Energy-based Forwarding Strategy for named data wireless ad hoc networks. *IEEE Access: Practical Innovations, Open Solutions*, 5, 6075–6086. doi:10.1109/ACCESS.2017.2684912
- Rehman, R. A., & Kim, B. S. (2015). Energy aware forwarding in content centric based multihop wireless ad hoc networks. *IEICE Transactions on Fundamentals of Electronics, Communications and Computer Science*, 98(12), 2738–2742. doi:10.1587/transfun.E98.A.2738
- Rehman, R. A., & Kim, B. S. (2017). LOMCF: Forwarding and caching in named data networking based MANETs. *IEEE Transactions on Vehicular Technology*, 66(10), 9350–9364. doi:10.1109/TVT.2017.2700335
- Ren, Y., Li, J., Shi, S., Li, L., & Chang, X. (2015). An Interest control protocol for named data networking based on explicit feedback. In *Proceedings of the 2015 ACM/IEEE Symposium on Architectures for Networking and Communications Systems* (pp.199–200). doi:10.1109/ANCS.2015.7110139
- Ren, Y., Li, J., Shi, S., Li, L., & Wang, G. (2016b). An explicit congestion control algorithm for named data networking. In *Proceedings of the 2016 IEEE Conference on Computer Communications Workshops* (pp.294–299). doi:10.1109/INFCOMW.2016.7562089
- Ren, Y., Li, J., Shi, S., Li, L., Wang, G., & Zhang, B. (2016a). Congestion control in named data networking—A survey. *Computer Communications*, 86, 1–11. doi:10.1016/j.comcom.2016.04.017
- Rezaeifar, Z., Wang, J., Oh, H., Lee, S. B., & Hur, J. (2019). A reliable adaptive forwarding approach in named data networking. *Future Generation Computer Systems*, 96, 538–551. doi:10.1016/j.future.2018.12.049
- Rozhnova, N., & Fdida, S. (2014). An extended hop-by-hop interest shaping mechanism for content-centric networking. In *Proceedings of the 2014 IEEE Global Communications Conference* (pp.1–7). doi:10.1109/GLOCOM.2014.7389766
- Ruiz, P., & Bouvry, P. (2015). Survey on broadcast algorithms for mobile ad hoc networks. *ACM Computing Surveys*, 48(1), 1–35. doi:10.1145/2786005
- Saino, L., Cocora, C., & Pavlou, G. (2013). CCTCP: A scalable receiver-driven congestion control protocol for content centric networking. In *Proceedings of the IEEE International Conference on Communications* (pp.3775–3780). doi:10.1109/ICC.2013.6655143
- Salsano, S., Detti, A., Cancellieri, M., Pomposini, M., & Blefari-Melazzi, N. (2012). Transport-layer issues in information centric networks. In *Proceedings of the second edition of the ICN Workshop on Information-Centric Networking* (pp.19–24). doi:10.1145/2342488.2342493
- Sarkar, S. K., Basavaraju, T. G., & Puttamadappa, C. (2013). *Ad hoc Mobile Wireless Networks: Principles, Protocols, and Applications* (2nd ed.). CRC Press.
- Saxena, D., Raychoudhury, V., Suri, N., Becker, C., & Cao, J. (2016). Named data networking: A survey. *Computer Science Review*, 19, 15–55. doi:10.1016/j.cosrev.2016.01.001
- Schneider, K., Yi, C., Zhang, B., & Zhang, L. (2016). A practical congestion control scheme for named data networking. In *Proceedings of the 3rd ACM Conference on Information-Centric Networking* (pp.21–30). doi:10.1145/2984356.2984369

- Tariq, A., Rehman, R. A., & Kim, B. S. (2019). Forwarding strategies in NDN based wireless networks: A survey. *IEEE Communications Surveys and Tutorials*, 22(1), 68–95. doi:10.1109/COMST.2019.2935795
- Thomas, Y., Fotiou, N., Toupmpis, S., & Polyzos, G. C. (2020). Improving mobile ad hoc networks using hybrid IP-information centric networking. *Computer Communications*, 156, 25–34. doi:10.1016/j.comcom.2020.03.029
- Udugama, A., Zhang, X., Kuladinithi, K., & Goerg, C. (2014). An on-demand multi-path interest forwarding strategy for content retrievals in CCN. In *Proceedings of the 2014 IEEE Network Operations and Management Symposium* (pp.1–6). doi:10.1109/NOMS.2014.6838389
- Vusirikala, S., Mastorakis, S., Afanasyev, A., & Zhang, L. (2016). *Hop-By-Hop Best Effort Link Layer Reliability in Named Data Networking*. Technical Report NDN-0041, NDN.
- Wang, Y., Rozhnova, N., Narayanan, A., Oran, D., & Rhee, I. (2013). An improved hop-by-hop interest shaper for congestion control in named data networking. *Computer Communication Review*, 43(4), 55–60. doi:10.1145/2534169.2491233
- Xin, Y., Li, Y., Wang, W., Li, W., & Chen, X. (2016). Content aware multi-path forwarding strategy in Information Centric Networking. In *Proceedings of the 2016 IEEE Symposium on Computers and Communication* (pp.816–823). doi:10.1109/ISCC.2016.7543837
- Ye, Y., Lee, B., Flynn, R., Murray, N., & Qiao, Y. (2017). B-ICP: Backpressure Interest Control Protocol for multipath communication in NDN. *Proceedings of the GLOBECOM, 2017*, 1–6. doi:10.1109/GLOCOM.2017.8254707
- Yi, C., Afanasyev, A., Moiseenko, I., Wang, L., Zhang, B., & Zhang, L. (2013). A case for Stateful Forwarding plane. *Computer Communications*, 36(7), 779–791. doi:10.1016/j.comcom.2013.01.005
- Yi, C., Afanasyev, A., Wang, L., Zhang, B., & Zhang, L. (2012). Adaptive forwarding in named data networking. *Computer Communication Review*, 42(3), 62–67. doi:10.1145/2317307.2317319
- Zhang, F., Zhang, Y., Reznik, A., Liu, H., Qian, C., & Xu, C. (2014a). A transport protocol for content-centric networking with explicit congestion control. In *Proceedings of the 23rd International Conference on Computer Communication and Networks* (pp.1–8). doi:10.1109/ICCCN.2014.6911765
- Zhang, F., Zhang, Y., Reznik, A., Liu, H., Qian, C., & Xu, C. (2015). Providing explicit congestion control and multi-homing support for content-centric networking transport. *Computer Communications*, 69, 69–78. doi:10.1016/j.comcom.2015.06.019
- Zhang, G., Li, Y., & Lin, T. (2013). Caching in information centric networking: A survey. *Computer Networks*, 57(16), 3128–3141. doi:10.1016/j.comnet.2013.07.007
- Zhang, L., Afanasyev, A., Burke, J., Jacobson, V., Claffy, K. C., Crowley, P., Papadopoulos, C., Wand, L., & Zhang, B. (2014b). Named data networking. *Computer Communication Review*, 44(3), 66–73. doi:10.1145/2656877.2656887

ENDNOTES

- ¹ <http://ieeexplore.ieee.org>
- ² <http://journals.sagepub.com>
- ³ <http://scholar.google.com>
- ⁴ <http://www.acm.org>
- ⁵ <http://onlinelibrary.wiley.com>
- ⁶ <http://www.emeraldinsight.com>
- ⁷ <http://link.springer.com>
- ⁸ <http://www.sciencedirect.com>

Dimitris Kanellopoulos is a member of the Educational Software Development Laboratory in the Department of Mathematics at the University of Patras, Greece. He received a Diploma in Electrical Engineering and a Ph.D. in Electrical and Computer Engineering from the University of Patras. Since 1990, he was a research assistant in the Department of Electrical and Computer Engineering at the University of Patras and involved in several EU R&D projects. He is a member of the IEEE Technical Committee on Multimedia Communications. He serves as a reviewer for highly-respected journals such as Journal of Network and Computer Applications (Elsevier), Int. Journal of Communication Systems (Wiley), J. of Systems and Software (Elsevier), Information Sciences (Elsevier), IETE Technical Review (Taylor & Francis) etc. He has served as a Technical Program Committee member to more than 100 int. conferences. His research interests include: multimedia networks, mobile ad-hoc networks, wireless sensor networks, and TCP variants for congestion control. He has many publications to his credit in int. journals and conferences at these areas. He has edited two books on Multimedia Networking and one book on MANETs and VANETs. He serves as an editorial board member in some refereed journals such as Electronics(MDPI) and Sensors(MDPI).