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DOCTORAL THESIS

A Study of Routing Protocols for Ad-Hoc Network Based on Named Data Networking

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A Study of Routing Protocols for Ad-Hoc Network Based on Named Data Networking

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Abstract

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by Minh NGO

With the developing of the smartphones and wireless technology leads to the increasing of application and services for mobile network, TCP/IP model has limitations in the transmission range, resources and mobility of node. Information Centric Networks (ICN) was introduced a promising new network architecture that more suitable for content distribution and Named Data Networking (NDN) has been widely researched as a sub-class of ICN research which focus on name of the content. In contrast to TCP/IP based network, the fundamental of NDN is adopting name of desired content instead of address of content provider (IP Address). Differ with IP packet, NDN uses two type of packet named Interest and Data represent for requesting and responding process. Content requester or called Consumer send Interest includes the name of desired content to retrieve. Content provider or called Producer which satisfies the request will return corresponding Data back to the Consumer. Furthermore, intermediate node where Data passed through able to cache that Data for future redistribution. At first, NDN is an architecture of wired network topology, but based on the advantages such as flexible multicasting or in-network caching, NDN shows various benefit of implementing on wireless ad hoc network. Due to the mobility of node, topology of network is changed frequently leads routing protocol has more research trends and more challenge than wired networks. Routing on NDN is the way to construct Forwarding Information Base (FIB) for name prefixes, which specifies the correspondence between a name prefix and a face (or a neighbor identifier) to the content with this name prefix. Therefore, there are many approaches to implement NDN based protocol to Wireless network. However, these approaches are not always effective in NDN because they have limitations on traffic overhead, mobility of node factor and neighbor identifier of NDN.

In this thesis, we propose two effective approaches to mitigate the network communication overhead for Mobile Ad Hoc Network based on NDN architecture and dealing the issue of NDN Face logic on Wireless Network to prevent the broadcast nature communication on each MANETs and VANETs scenarios separately.

First, on MANETs scenario when mobile nodes is small devices such as smartphones and tablet that low mobility and movement direction is random, we provide a hybrid approach by combining proactive and reactive based protocols. We divide network into a consumer side contains mobile nodes and a producer side contains the fixed node. The producers side has powerful resources and stable network so we offer a proactive routing based on this side focuses only on the name prefix advertisement. On the other hand, the mobile has limitation of resource and energy instead of maintaining the route, consumer side provide a reactive-based routing where nodes do not use any control packets for routing. By this way the request is quick-searched once it reach to producer side to reduce network traffic overall. Furthermore, we also use MAC Address replaces FACE notion to operate unicast-based communication to deal the default NDN's architecture issue. Through the simulation experiments, our first approach mitigated packet overhead overall compares to pure proactive and reactive method.

Second, in case of VANETs scenario we introduce a content retrieval during traveling, vehicle wants to check the road conditions ahead in a light-weight and robust way by supporting full unicast communication protocol. Based on the manner of beacon-based method to operate a unicast communication, we provide a unicast-based forwarding on a beaconless manner by using font/rear cameras to identify Node ID based on visual information. New node identifier called visual identifier (VI) is core of our design, when vehicle captures visual information such as number plate numbers, color, brand, type to build VI. Vi is unique and obtained in an active way helps to provide a robust unicast communication. Furthermore, To improve the accuracy of routing and forwarding, we also introduce a check before transmit mechanism by using always on camera of vehicle to keep monitor running around nodes in real-time. Through the simulation experiments, our second approach mitigated packet overhead, high delivery ratio and also capable to deal the movement issues of vehicular network.

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Contents

List of Figures

List of Tables

Chapter 1

Introduction

1.1 Background

The core of current Internet is developed by Internet Protocol (IP), which performs an end-to-end packet delivery based on IP addresses of client and server. The nature of IP address represents to a unique identifier and logical location of node on Internet. In particular, IP assigns the header includes the source and destination information of the packet that helps for routing and forwarding all the packets that be transmitted through the network [1].

Originally, node on Internet was only static personal computer or network devices and connected through wired network. However, with the rapid growth of mobile devices and emerging wireless technologies, TCP/IP became less effective due to the dynamic topology of wireless network [2]. For instance as shown in Figure 1.1 once a node joins and leaves one network, IP address has to be changed to connectable within the new network. TCP/IP over-rely on the location of nodes for building an end-to-end path, this approach is easily broken in case of mobile devices network such as smartphones. Furthermore, the increasing number of nodes leads to the damage of the traditional client-server communication, amount of same content request to the server is redundant and wasting bandwidth [3].

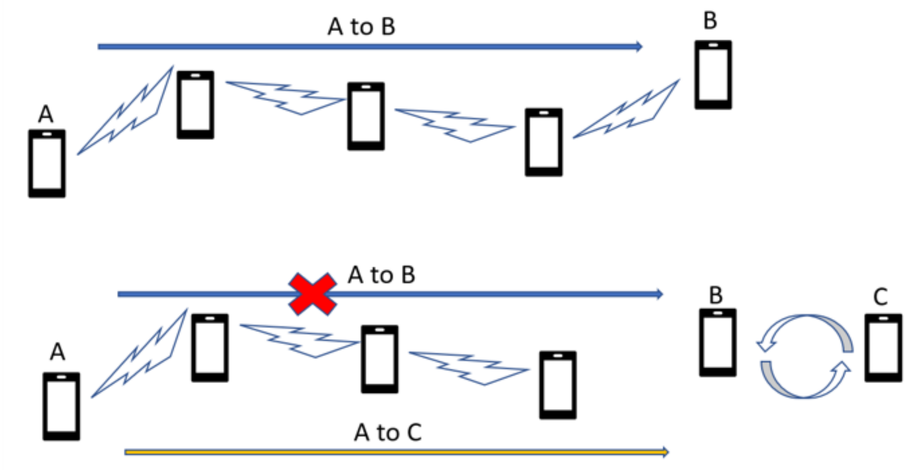


Figure 1.1: The current IP-based Network.

Therefore, instead of IP dependence approach, a promising Internet architecture paradigm has been proposed recently called Named Data Networking (NDN). NDN is a variant of Content Centric Networking (CCN) for dealing with the issue of content location on traditional IP network [4]. NDN offers a smart way on-demand approach similar to the logic of real-world application and services where on content delivery, the "content" is re-defined by its name rather than its location. Hence, NDN is a canđiate for the future of Internet architecture where content is delivered and propagated among nodes via only unique content name.

In addition, with the developing of the smartphones and wireless technology leads to the increasing of application and services for mobile network, TCP/IP model has limitations in the transmission range, resources and mobility of node. Mobile Ad Hoc Network (MANET) is introduced as a solution to deal these issues [5-7]. MANET is a infrastructure-less network where node communicate with other nodes directly, in the aspect of client-server relationship, a node has both roles of client and server simultaneously. MANET has advantages in scalability of network scenarios compared to the fixed network-based due to its decentralized nature, self-configuration and quick operations [8]. However, the traditional MANETs is based on TCP/IP protocols that still be questioned about able to support a stable end-to-end communication. In fact, MANETs is affected due to fast-changing topology and battery constrains makes node is off causes packet loss especially in vehicular network where the velocity of moving node is much higher than mobile devices like smartphones [9]. For instance, during the time between two update, although the receiver node is out of range, packet still keeping be sent out from the sender and lost until the next updated state. Furthermore, the most easiest solution to deal this issue is using unreliable and lossy communication to broadcast all the packet to improve the delivery chance. Based on the considerations about issues of current MANETs, applying NDN architecture to MANET is emerged in recent years as a suitable solution for future network.

Differ to TCP/IP once a end-to-end route is broken the entire current route is discarded and a new route to destination will be recovered, NDN has capability to support mobility network by re-routing intermediately by any node that satisfied the request without re-locating the provider [10] as shown in Figure 1.2. Alternatively, NDN is rely on the requested information rather than the location of node that the any intermediate node can become a provider, the provider is multi-choice and flexible. Although applying NDN to wireless network has many advantages, extremely high request packets can cause congestion and packet redundancy problems [11-13]. There are two reasons of high packet count that can be recognized. First, in the default of NDN behavior, the requester floods the first request and all participate nodes costs amount of request packet to discover the provider and recover the route when the link is broken. Second, the benefit of location independent causes a logic problem in NDN when mobile node has only one WIFI interface, the incoming stream and outgoing stream is combined into one leads to all the communication becomes broadcast.

This thesis addresses two challenges and propose solutions for routing process in NDN based MANETs. We describe these problem statements together with our contributions of this thesis in the following sections

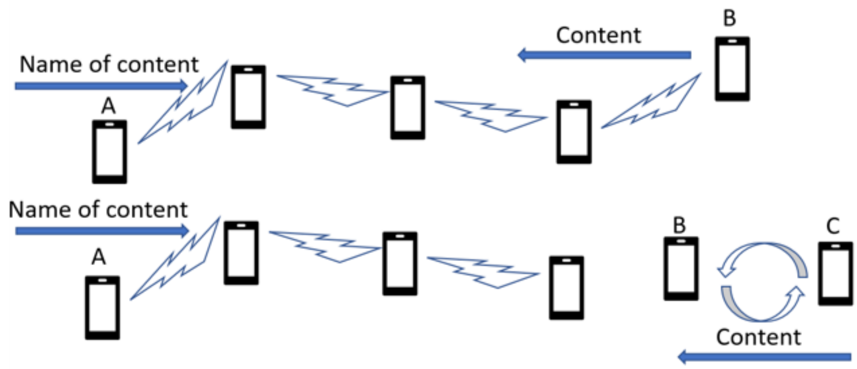


FIGURE 1.2: The new NDN network.

1.2 Research Questions

Our study aims to mitigate network communication overhead for Mobile Ad Hoc Network based on NDN architecture and dealing the issue of NDN Face logic on Wireless Network to prevent the broadcast nature communication in the followings.

Broadcast storm occurs when multiple nodes attempt to transmit at the same time with large amount of data in shared media, this problem is resulted by flooding-based data dissemination in Wireless network [14].

In Ad hoc, node communicates with other nodes directly that makes the connectivity among nodes is the most critical element for building a service based on wireless ad hoc network. In particular, the topology of mobile nodes is changed frequently leads to the unstable network connection, the risk of packet loss is is highly increasing. Many functions on Wireless ad hoc network such as routing is based on broadcast manner when node attempt to send out the message to entire nodes on network. It is considered as a most reliable strategy of communication with some reasons. First, broadcast is able to coverage maximum reachable nodes to improve the chance of delivered data. Second, its receiving and flooding manner that saving the packet processing resources. Finally, broadcast also suited with high mobility network where the link between nodes be disconnected frequently.

However there are some back draw of this method that is challenging many current researches. Broadcast wastes a amount of network and node resources when keep transmitting all the time that decrease the bandwidth and throughput of network. Secondly, due to broadcast leads to message collisions in the communication channel, thus important services is unsatisfied content retrieval attempts (safety application) [15]. Implementing NDN to wireless networks has many advantages to deal these issues as mentioned on previous section, after all it still has several following limitations considered as our research questions.

First, on NDN when node wants to retrieve a content as shown in Figure 1.3, it has to initial a request and send out to discover the content, any receiver which able to satisfy this request will return the content back to the requester. Due to the knowledge of network is blank at the beginning, only the first request packet has to be transferred by broadcast based to all nodes and called flooding phase. Furthermore, this flooding-based content discovery phase and will be reactive when a new content is required or due to the topology change, the subsequent request of the same content unable to delivered successfully and new route is required (discovery phase). Therefore, the first research question (**RQ1**) is **how to mitigate the overhead on content delivery in MANET.**

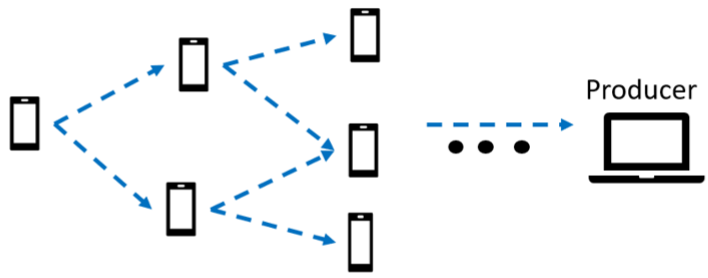


FIGURE 1.3: Consumer requests content from Producer.

Second, NDN is a new architecture which is originally designed for wired network such as network devices as shown in Figure 1.4. In contrast to IP-based network where name of content is maintained rather than location of content holder, node just sent out packet to one FACE (outgoing-face) and receives packet from another FACE (incoming-face) separately without caring where this packet send from or send to. A wired node have multi-interface is able to handle this easily, however in wireless environment where node commonly has only one WIFI interface, the logic of Face is conflicted. The IN and OUT of Face become the same leads to broadcast frames on the data link layer naturally. Furthermore, the function of NDN about routing, forwarding and and caching unable to work correctly. Therefore, we consider our second research question (**RQ2**) is **how to mitigate the broadcast transmission on FACE logic problem of NDN based wireless ad hoc network.**

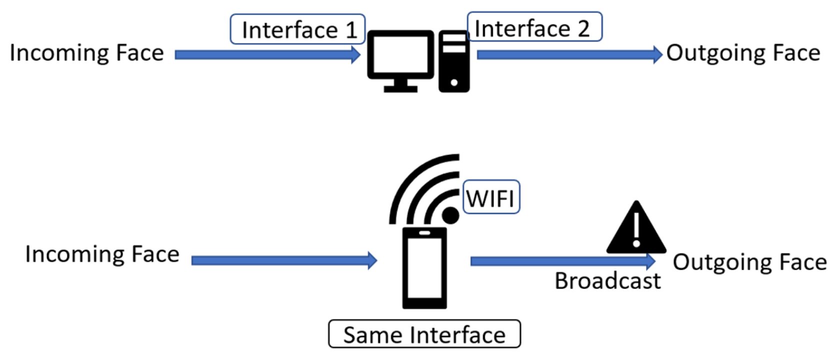


FIGURE 1.4: Face logic problem.

1.3 Thesis Contributions

We design two NDN based approaches addresses two research questions mentioned above for MANETs on each typical services of mobiles devices and vehicular.

First, in case of MANET we introduce a protocol for supporting public network on MANETs such as shopping malls, museum or park etc. In this typical content distribution services, this local content like bargain, guide or video streaming and provided by multi servers located on that area. The moving nodes and fixed nodes are coexisted and content is reused frequently are two key characteristics of this system. According to these considerations to answer RQ1, we divide NDN network to two parts: producer and the consumer side. The Producer side has all the producers and intermediate routers with fixed location characteristic. On this side the link is stable so we offer a proactive routing based on this side focuses only on the name prefix advertisement. Each producer constructs a directed cyclic graph (DAG) to advertise its content. Information of content is shared and updated among producer side frequently. On the other hand on the consumer side, the mobile nodes such as smartphones has limitation of resource and energy instead of maintaining the route, consumer side provide a reactive-based routing where route is generated on demand. First Interest will be flooded into consumer side to discover the content until arrives any node belongs to producer side, Interest will be forwarded to the producer based on maintained routing information on Producer side (broadcast to unicast switching). Once Interest satisfied Producer was found, the Data will be return to original Consumer and s set of temporary FIB entries were created on nodes of Consumer side simultaneously. The following is Interest of same content can be forwarded by the route which already built by first Interest. Furthermore, we also use MAC Address replaces FACE notion and implement the detail on NDNSim simulator to address the RQ2. In our design, since packet passes on intermediate nodes, the MAC address of sender is captured and added into PIT, node looks up FIB for next hop MAC address, puts into destination MAC-address and source MAC address field by its MAC-address, a set unique identifier of sender and receiver will be used for unicast-based communication. For performance evaluation, we compare of hybrid method with a pure reactive (REMIF) and proactive method (TOP-CCN).

Second, in case of vehicular network where has several special characteristics compares to normal MANETS such as the mobility of node is much higher but the movement is predicable and more powerful resources that required another appropriate protocol. In VANETS the safety information is the most critical content that should be updated periodically leads to the cost of network traffic. Based on these considerations, we provide a lightweight and robust protocol to answer the RQ1 and RQ2 for vehicular network. Instead of using MAC address or Node ID on beacon-based approach, our design leverages on front/rear cameras to identify a new identifier of node based on visual information such as number plate numbers (highest priority) and extended factors like color, brand, type etc. named visual identifier

(VI). By this lightweight way vehicle does not rely on beacon and able to choose the next-hop among all neighbors on the line of sight, provides all unicast forwarding freely. In addition, due to the dynamic of network, receiver is out of service while sending message that leads to packet loss. To improve the accuracy of routing and forwarding, we also introduce a check before transmit mechanism by using always on camera of vehicle to keep monitor running around nodes in real-time . Once before sending any packet, node has to check the available of next-hop to prevent packet loss and as the result, our design mitigates the loss, delay and traffic entire network. In case of vehicular objects, we evaluate the performance of our method compares to a beacon-based method (NDN based GPSR) and a pure NDN method which used MAC address as the Node ID (MMM-VDN).

1.4 Thesis Outline

The remainder of the thesis is organized as follows.

Chapter 2 describes the technical background of our research regarding to Wireless Ad Hoc Network and Named Data Networking (NDN) concept. We also review some previous works that adapt to implement NDN architecture in both Mobile Ad Hoc Network (MANET) and Vehicular Ad Hoc Network (VANET).

Chapter 3 addresses RQ1 by proposing a protocol for typical ad hoc network used in local area such as shopping malls and museums where amount of Consumer periodically request content from limited number of Producer. Based on the characteristics of mobile Consumer is moving around frequently, on the other hand the Producer is a number of fixed interconnected router and have stable connection, we divide network into Consumer side and Producer side and each side adopts proactive and reactive approach routing separately to reduce the routing burden for the mobile nodes. We also answer RQ2 by utilizing MAC address instead of Face as a unique ID of node to provide a hop-by-hop forwarding scheme of our protocol. Our Hybrid approach eliminates broadcast transmissions are shown on the results of performance evaluation section.

Chapter 4 addresses RQ2 by introducing a novel of forwarding messages based on visual identification replace to previous MAC Address method. We use a beaconless method to maintain neighbor nodes by using camera to capture visual characteristics of running around vehicle such as number plate, color, brand etc. to assign a simple and unique ID called Visual Identifier (VI) for each vehicle. For RQ1, VI replaces FACE notion to fully support unicast forwarding on our design. Furthermore, camera vision we also able to recognize the front or behind vehicle to prevent the flat-forwarding problems. Finally, we introduce a check before transmit mechanism to encounter the broken link on real-time manner. important directions

Finally, chapter 5 concludes our thesis contribution and discuss the necessary direction of future work.

Chapter 2

Related Work and Technical Background

In this chapter we describes the major themes of this thesis arose from three main concepts: Mobile Ad Hoc Network (MANETs), and Vehicular Ad Hoc Network (VANETs) and Named Data Networking (NDN). In addition, we review the state of the artwork and their combination that related to our research.

2.1 Mobile Ad hoc Network

Recently, due to the rapid growth of mobile devices and technology, application in wireless communication, Mobile Ad Hoc networks (MANETs) is emerged as one of the promising solution for future wireless networking systems.

2.1.1 Overview of MANETs

Differ with the cellular network that base station is required and acts as an access point, MANETS is based on Ad Hoc network where nodes can move freely in all directions, mobile nodes in VANETs do not relay on a infrastructure and can directly communicate with other nodes. According to the advantages of MANETs such as costs, flexibility, mobility and infrastructure-less, MANETs is suitable for several systems such as local-level services, military, emergency services, vehicular communication etc [16].

Figure 2.1 shows an example MANETs where four devices communicate with each other in transmission range, node 1 and 3 in range of node 2 that node 2 can directly communicate with node 1 and 3. Furthermore, node 1 able to extend the transmission range to node 3 by relay the packet on node 2 . Node 3 is unable to communicate with Node 4 because of transmission range and have to wait until it moves closer to others .

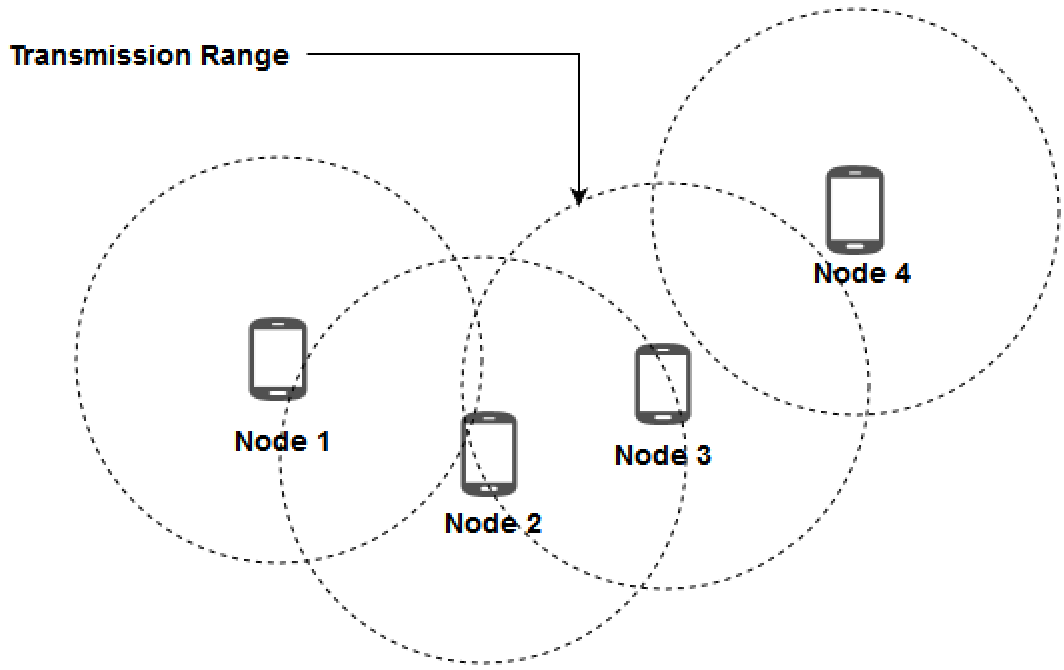


FIGURE 2.1: Mobile Ad-Hoc Network.

However, MANET has some issues are still considered as research challenges:

• Power constraint: Node in MANETs such as smartphone or table has limitation of power resource.

• Bandwidth constraint: The transmission range is short has led to the impact of fading, multi accesses and interference to communication.

• Dynamic Network topology: Network topology is temporary and changes randomly at any time.

2.1.2 MANET routing protocols classification.

The mobility of nodes and high dynamic network are considered as the most problems on MANET that make routing decisions more complications compares to wired network. Many MANET researches have been suggested [17-19]. According to the routing protocol's operation and our aim is focusing on how to maintain the forwarding/routing table, routing protocol in MANETs can be classified into two main types: Proactive routing (table-driven) and Reactive routing (on demand) as shown in Figure 2.2 . The comparison of two approaches is summarized in the following Table 2.1.

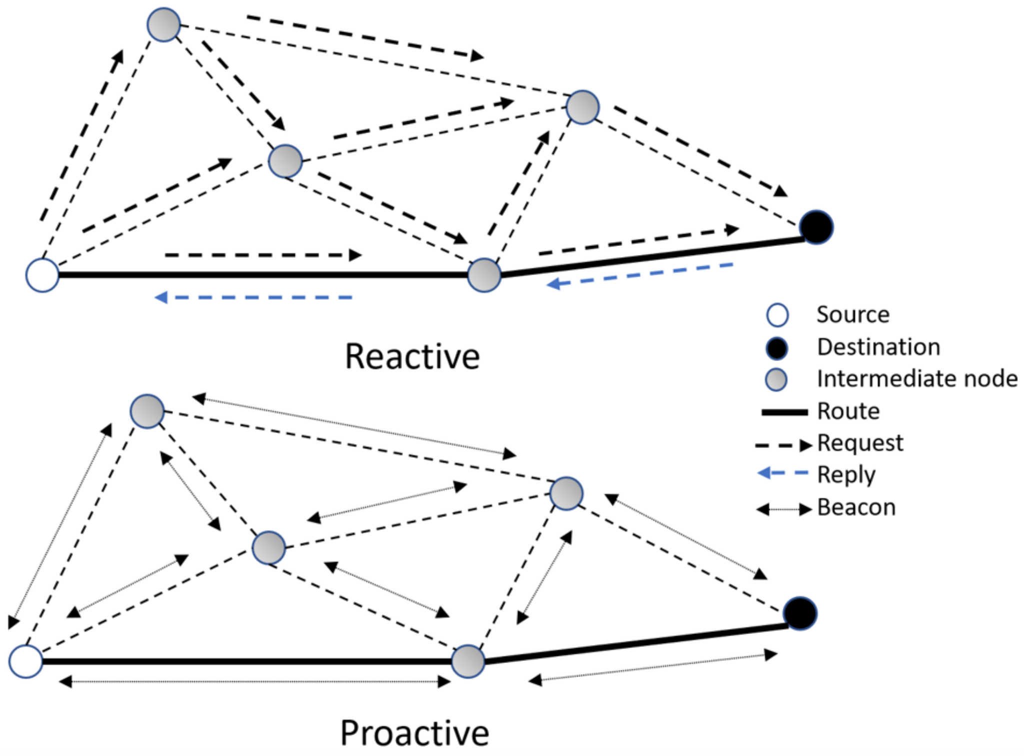


FIGURE 2.2: Reactive and Proactive protocol.

TABLE 2.1: Comparison of Reactive and Proactive Routing Protocol.

Parameters	**Reactive**	**Proactive**
Routing	Flat	Flat/Hierarchy
Routing Overhead	Low	High
Latency	High	Low
Scalability	Small Network	Large Network
Periodic Update	No	Yes
Mobility Support	Route maintenance	Periodic update
Routing Information Availability	Available when required	Always available
Control Traffic	Low	High

Reactive Routing.

In Reactive Routing protocols is basically considered as an on-demand approach, the route will be established only when a source requests a route to its destination (on-demand). The source will initiate a route discovery procedure by flooding the route request. Every immediate node that received this packet will rebroadcast until it arrives destination node or a node has the route corresponds to destination. There are various types of reactive routing protocols in ad-hoc network such as Ad-hoc

On-demand Distance Vector routing (AODV) [20], Dynamic Source Routing (DSR) [21], Temporary Ordered Routing Algorithm (TORA) [22] etc.

Ad-hoc On-Demand Distance Vector Routing (AODV) [20]

Ad-hoc On-Demand Distance Vector Routing (AODV) is a pure reactive protocol or on-demand routing protocol. Node does not maintain any routing information until the route discovery is active when needed. There are three main objects in AODV process:

- Route request
- Route reply
- Route and connection maintenance

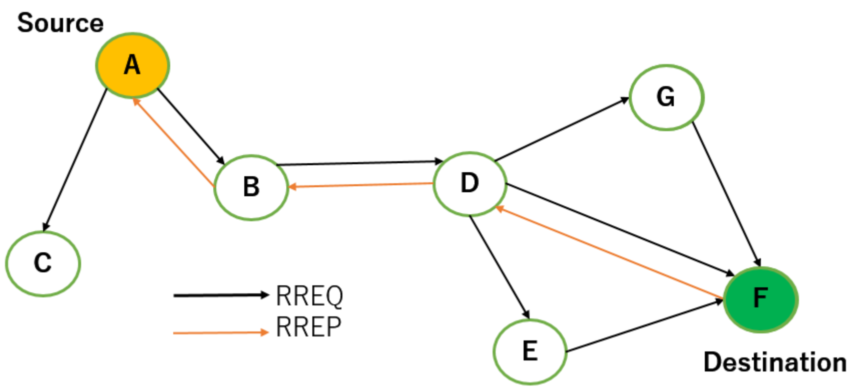


FIGURE 2.3: AODV Routing and Forwarding.

Route request phase: Node generates a route discovery process by flooding a route request (RREQ) packet to all connected neighbors when it wants to send data to a new destination if a valid route information founded in the routing table. RREQ will be rebroadcast in each relay node until it arrives the destination or node has route information point to destination. RREQ includes IP address of source and destination, sequence of source destination, broadcast-ID, and hop count. Once the relay node transmits an RREQ has the same broadcast ID of same source node, this packet is considered as a duplicated packet and will be dropped to prevent redundant traffic.

Route reply phase: When RREQ reaches the destination or a relay node that has a routing information corresponds to destination, the node replies a packet called Route Replies (RREP) to the node that sent RREQ by unicast. RREP includes source and destination addresses, destination sequence, hop count and lifetime. RREP will be returned back to the original source by reverse path and also use symmetric links to create the route entry in their routing table .

Route and connection maintenance phase: As mentioned above, as long as the route is being used, route maintenance will continues. If a source moves out and the route will broken, a route recovery process to find a replacement route will be active. Route Error (RERR) packet is generated once unreachable node or link failure occurs. RERR packet is then broadcasted to the neighbor nodes on the precursor list of destination until it arrives to original source. The source node will make a decision to stop sending data or initiate a route recovery process to find a replacement route if still needed.

Proactive Routing.

In contrast to reactive routing protocols, proactive routing or table driven routing protocols maintains a table representing the entire network topology (route from each node to every other node). The table is updated by topology information exchange procedure between nodes to make the route always available on receiving a request. However, the procedure has a trade-off of high overhead to the network. Notable proactive protocols are Optimized Link State Routing Protocol (OLSR) [51], Destination-Sequenced Distance-Vector Routing (DSDV) [52], Wireless Routing Protocol (WRP) [23] etc.

Optimized Link State Routing Protocol (OLSR) [51]

On MANET, the most typical proactive protocol is Optimized Link State Routing Protocol (OLSR). Node stores the route to all destinations on network and also periodically advertises the information about links to its current neighbors (control packets) in broadcast approach. OLSR works in a full distributed manner without depending on central control. Control message is exchanged periodically and does not concern about reliability. To mitigate the flooding control messages, in OLSR every node (node n) have to select among a set of its one-hop neighbors called Multipoint Relays (MPR), which can cover all two-hop neighbors. Only MPR can re-transmit the received packets from node n to minimize duplicates transmissions.

There are two main types on the control message in OLSR corresponding to two major stage:

- HELLO message (link sensing)
- TC (Topology control) message (topology sensing)

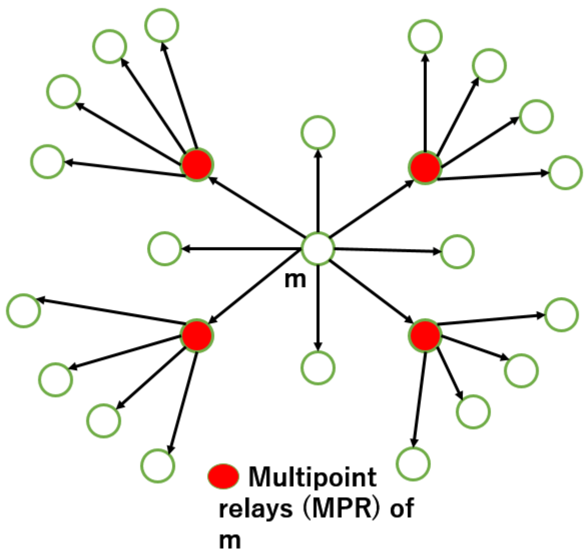


FIGURE 2.4: Broadcast packets forwarded by MPR.

First stage (link sensing): Each node sends HELLO message to its direct neighbor in broadcast mode every 2 second to determine status of links, and this message cannot be rebroadcasted to further nodes. A HELLO message contains message types, originator address, valid time and one-hop neighbors of the originator. By using the neighbor list in received HELLO message, nodes can discover their two-hop neighbors. Information in HELLO message allows each node to create a neighbor table (MPR set). Node n elects among its neighbors a set of nodes as multi-point relays (MPR(n)), which can rebroadcast control packets from node n. A MPR(n) must satisfy the two following conditions: (1) Have the transmission range to all the two-hop neighbors. (2) The numbers of MPR should be a minimum to prevent overhead in the network. The MPR set will be recalculated in addition when a change of one-hop neighbor or two-hop neighbor detected.

Second stage (topology sensing): The Topology Control (TC) message is broadcasted every 5 second to build the intra-forwarding database and will be rebroadcasted only by the MPRs node. Information in TC message allows each node creates topology table individually and also selects a set MPR selectors. Among MPR selectors one node will chosen as a MPR and information of MPR selectors will be added into TC packet. Based on information of TC packet, node builds a topology table contains possible destination, last-hope node to destination, MPR Selector Set sequence numbers. By this way the path to destination node can be created by the originator of TC message.

2.1.3 Vehicular Ad Hoc Network

Vehicular Ad Hoc Network (VANETs) is a special class of MANETs that adopts the advances of wireless ad hoc technology and automotive technology. VANETs is the core network technology to provide safety and comfort driving system in vehicular environment [24].

VANETs are Ad-hoc based networks thus mobile nodes are self-configurable and dynamically make the paths among themselves to transmit packet either relying on infrastructure. They will able to exchanges information beyond their immediate surroundings or allowed to communicate with roadside units to obtain interest data thus we divide communication into 3 categories as shown in Figure 2.5:

• Vehicle-To-Vehicle (V2V) network: The Communication among vehicles without relay on infrastructure with mainly support for critical safety and dissemination applications. Two approaches in this data dissemination pull-based and push-based. When to spread information to all vehicles such as advertisement or safety road information, Roadside Units will broadcast data to all vehicles within its communication range in push-based approach, on the other hand when vehicle want any interest such as forecast or local map information vehicles are enable to request information about specific data and response by unicast in pull-based approach.

• Vehicle-To-Infrastructure (V2I) network: The communication between Vehicles and Roadside Units (Access point or base station) with mainly support for interest data and gathering applications. In V2V communication, the vehicles organize ad-hoc network among themselves rather than relay on infrastructure. Flooding approach means to broadcast data in a network, this approach is suitable for sparse network and sensitive low-delay applications. In relaying approach, sender node will select the relay node to forward data, the advantages of this method is reduce congestion and scalable to dense networks but high delay depend on the numbers of relay nodes.

• Hybrid architecture: Combining V2V and V2I, Vehicles can communicate with roadside units and also short-range local communication. In the opportunistic approach, data is stored and carried across network partitions, suitable for dynamically topology but its drawback is increasing the delay in data delivery.

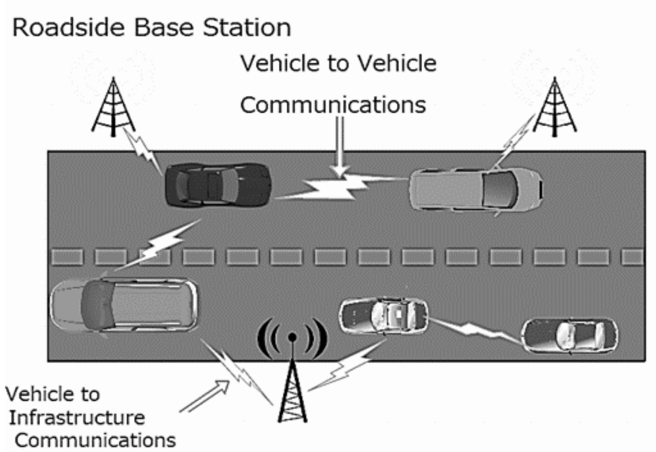


FIGURE 2.5: Vehicular Ad Hoc Network communications.

Basically, routing protocols in VANETs can be classified into Topology-based protocol and Geographical-based protocol, the broadcast-based and unicast-based routing is adopted by each method individually. Similar to MANETs, the topology-based protocols in VANETs maintain the knowledge of universal connectivity of network and has two main sub-categories are proactive and reactive protocol. However, topology-based protocols is not suitable for high mobility network such as vehicular nodes, proactive approach is challenged when the cost of maintenance of routing information is extremely high. Beside, reactive approach is suffered from high latency due to delay to discover the route to destination. Furthermore The movement of nodes has impact on the communication in Wireless network especially in Vehicular network.

In MANETs the mobile nodes moves freely in any direction with low speed, on the other hand, VANETs has a high velocity mobile nodes and predictable moving direction. Thus on VANETs, Geographical-based [25] is proposed as a most suitable approach for dynamic network that the path is established hop-by-hop to best-effort forward the packet to destination. Differ to topology-based protocol, the core used information is the position of node that related to the movement factor. Node maintains its location by using Global positioning system (GPS) and deliver the packet by the knowledge of other node's positions as shown in Figure 2.6. Hence, on geographical-based approach, the maintaining routing information is considered as a not required action, node obtains the position of in range of transmission nodes by periodic exchanged beacon messages, calculates and selects among them a best-metric node able to forward the packet. Geographical routing is commonly used in VANETs due to suitable with high dynamic network topology. The geographical-based routing is divided into two types: Delay tolerant networks protocols (DTN) and Non-delay tolerant networks (non-DTN) [20]. The comparison of the protocols is summarized in the following Table 2.2.

FIGURE 2.6: Geographical Forwarding.

Delay tolerant networks protocols (DTN)

The main concept of Delay tolerant networks (DTN) is store, carry and forward [27]. In situation unable to communicate with other nodes, node keeps the packet until meets another next-hop to pass this packet to relay. The motivation of this method is designed to deal with the technical problems that damaged by disconnections due to the high mobility. By this way, DTN provides a less packet-loss but increases the delay for packet forwarding due to the packet holding behavior. DTN is suitable for the high delay information such as for traffic information or infotainment.

Non-Delay tolerant networks protocols (DTN)

In contrast of DTN, non-DTN protocol is a best-effort delivery approach that attempt to forward packet to the destination as fast as possible [28]. Non-DTN protocol be classified into two subclass are beacon-based and beacon-less protocols. Beacon-less protocol provide a communication based on default TCP/IP model and position without using any control packet, due to this the packet is normally blind-forwarded into network until reaches to the destination. Beside, a beacon-based protocol usually use a packet called beacon to exchange the information about node ID, position, velocity etc. periodically to maintain neighbor tables. Based on these information, node calculates metrics for neighbors and when node want to transmit packet to a destination, it selects in Neighbor table a node that has the best metrics as candidate node. For instance, it calculates itself distance to destination and the distance of each neighbor to destination, node selects among its neighbors a node has best metric of distance as a candidate node.

Table 2.2: Comparison of DTN and Non-DTN Routing Protocol.

Parameters	**DTN**	**Non-DTN**
Survival Time	Short	Not concerned
Packet loss	Low	Dynamic
Space ratio	Reduce the space ratio	The bigger the better
Storage Capacity	High	Low

Problems of movement on VANETs

Due to the high mobility of Mobile Ad Hoc Network, the most common controlled broadcast approach is sender-oriented protocol, the sender find a appropriate relay node. Gathering the relative information of all neighbors, to reduce the number of relay-node as much as possible especially in dense networks. There are so many types of neighbor's information such as ID, velocity, number of connected nodes etc and be used to calculated the metrics to evaluate the best next-hop for forwarding. Among of these information, the movement of nodes has a large impact on the communication in Wireless network especially in Vehicular network. The movement factor includes three main sub-factors: position, speed and movement direction where position is the result of the other two factors. In MANETs the mobile nodes moves freely in any direction with low speed. On the other hand, VANETs has a high velocity mobile nodes and predictable moving direction. Hence, without focusing on movement factor while selecting the candidate node, packet forwarding failure occurs. There are some typical problems of movement on VANETs as shown in Figure below.

First is the problem of opposite direction, Figure 2.7 shows the white node of opposite direction is selected as the candidate node because it has a shortest distance to destination based on GPS positions. Nevertheless, the transmission will be lost due to the white node is moving on wrong direction to destination.

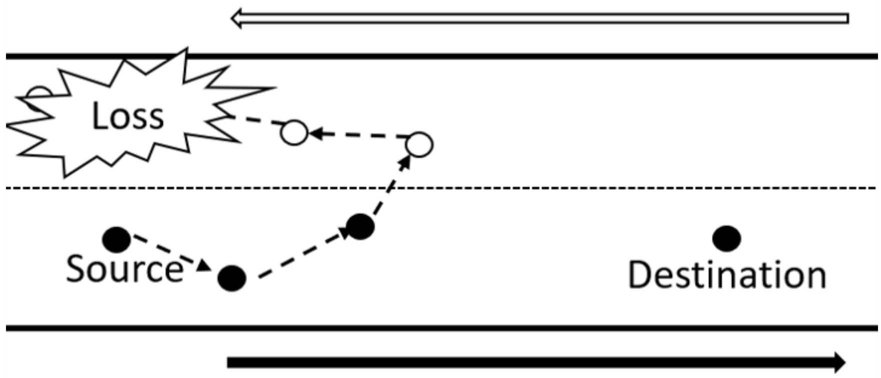


FIGURE 2.7: Opposite Forwarding.

The second is about the radio range, during the interval of neighbor information update the movement of mobile node can barely be changed. For instance, when the highly mobile node marked In Figure 2.8, we assume that the vehicle red is moving faster than the source node, so the red node will exceed the transmission of source quickly before packet was transmitted..

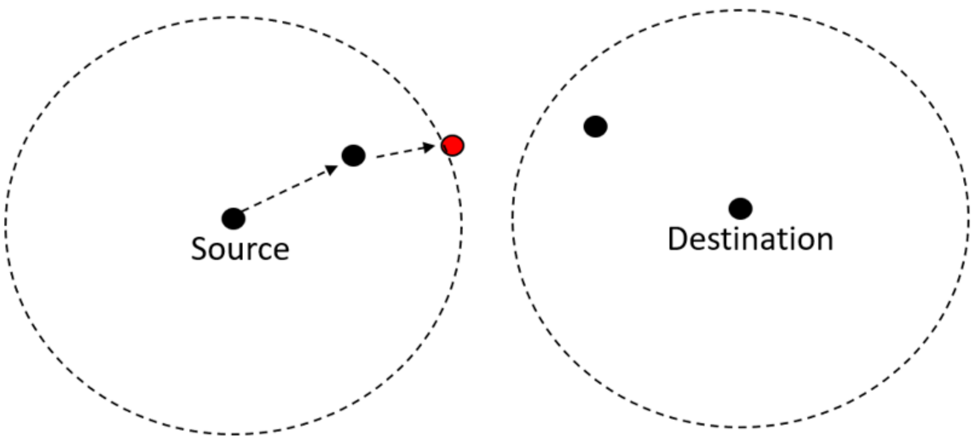


FIGURE 2.8: Unreachable Forwarding.

2.2 Named Data Networking

Named Data Networking (NDN) is a promising information-centric architecture for the future of Internet to achieve efficient content distribution. The original concept of Internet is an on-demand service, people care for "what" content it contains but the current Internet communication is still in term of "where". It means with current IP-based architecture, rather than Internet user being able to directly access to content faster and efficiently, they have to be concerned with global network information such as content holder location (IP Address). The motivation of NDN is shifting the information objects from host end-points to name [29].

2.2.1 IP-based Network vs NDN

The IP-based network provides a end-to-end communication between source and destination based on their location (IP-address) that similar to post-office services. When a node want to retrieve content, it is considered as a client and has to identify the location of destination via an address management agent such as Domain Name Server (DNS). Then the client sends a IP packet for requesting, this packet will be forwarded on intermediate nodes by using routing information until reaches to the server. Server accepts the request and transfers the content back to the client. Therefore, such kind of communication depends to the quality of the link and the capability of server. Thus, with the increasing of number of requests, the resources of entire network and also server exhausted linearly to handle all individual requests.

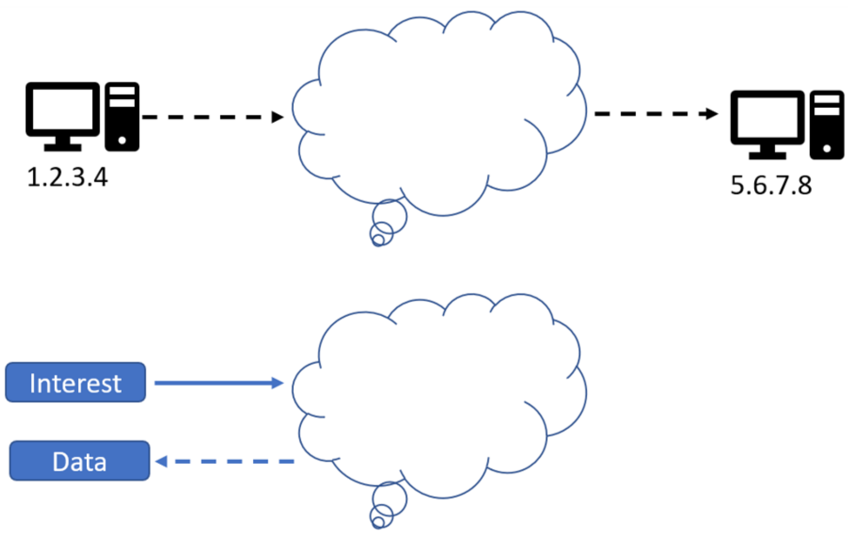


FIGURE 2.9: Host centric vs Content centric.

In contrast, NDN is a new content based architecture aims to re-define the core notion of Internet from address to name [30]. NDN replaces the traditional host-oriented communication in wired networks to content-oriented model which is a IP independent approach. Due to the location knowledge free paradigm, a NDN node sends request to upstream until retrieves the desired content. Then, any node in upstream satisfies this request and transfers the content to the client. Furthermore, NDN allows a copy of content to be cached on each node that the content passes to optimize the traffic of the same content request. This subsequently request can be satisfied quickly from any node which closer to Consumer than original Producer to reduce the burden for server and provide multi-path content delivery. Thus, only by name of the content, the content can be disseminated among nodes. NDN model is a promising architecture that suitable for decentralized network, scalable for intermittent connectivity and dynamic/mobile topology rather than IP network.

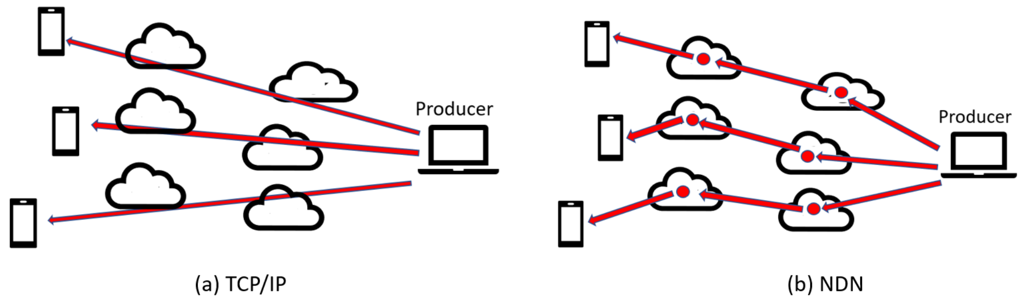


FIGURE 2.10: IP-based Network vs NDN.

NDN node uses two types of packet: Interest packet contains prefix of content requested and Data packet contains the content. A user (named Consumer) will request a content by broadcasting an Interest over all interfaces. Once node hears the Interest and has the appropriate content, node become a Producer and replies with a Data packet. A same content can be shared among multiple consumers. Nodes in the NDN architecture receive and distribute packets via connection points called "Faces", which is a typical view of a physical or logical network interface.

The basic operation of a NDN node is similar to an IP-based node. It maintains three data structures as below [31].

• Forwarding Interest Base (FIB): Similar to Routing Table of IP-based network, FIB includes route information for prefixes.

• Pending Interest Table (PIT): Do not existed on IP-based network, PIT stores the information about the pending Interest (not satisfied yet).

• Content Store (CS): caches received Data for future redistribution (in-network caching).

The Figure 2.11 is an example of NDN routing and forwarding process. Node A want a content then A initial generates a Interest 1 and send to outgoing FACE to discover the content. Node B and C belong to upstream receives Interest 1 and in order looks up their caches, put content name in PITs and continue re-forward Interest 1 to the upstream node of B and C is node D. The Interest 1 from C arrives first, Node D has the corresponding content then send a DATA back to C, the later

Interest 1 from B is already satisfied that discarded. DATA will forwarded by PITs of C and returns to the original consumer is node A, A also caches this DATA for further content dissemination. The following Node X when want to retrieve this DATA, X only send Interest 2 to A and directly receive from A without relayed to the original Producer is node D again.

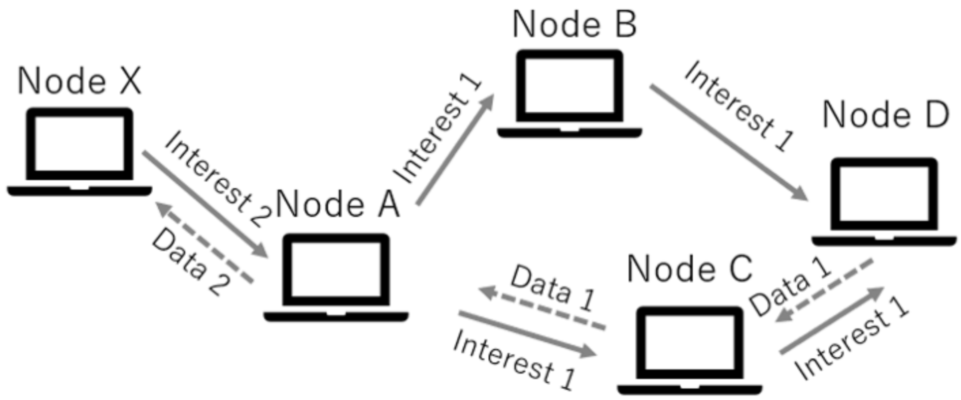


FIGURE 2.11: A example of NDN forwarding.

The Figure 2.12 shows the flow chart of one arrival Interest, Node checks the prefix name on Interest first. In case node has a replica of the content, node become a Producer of this content and sends Data to upstream back to original Consumer and discards this Interest intermediately. Otherwise node continues move to next process is checking its PIT, if a matching PIT entry was found, the Face of arrival Interest will be added into this PIT entry and discard the Interest. Otherwise, node looks up the FIB, if a FIB entry matches with name prefix was found, node transmit the Interest to the Face indicated by the corresponding FIB entry. Each PIT entry added can be used as the breadcrumb trail to send the data backs to the original Consumer.

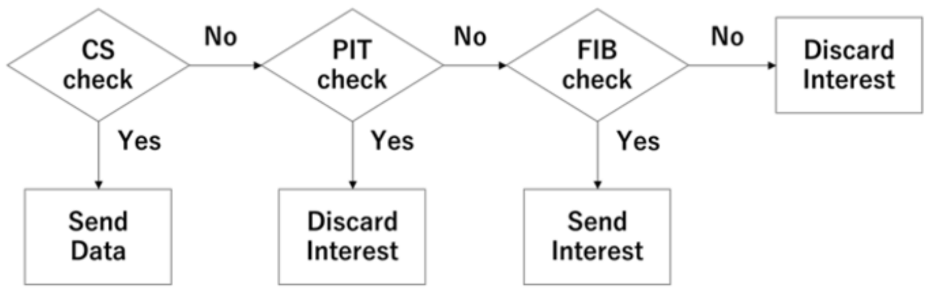


FIGURE 2.12: Forwarding Process in NDN.

Scalability of routing on NDN

IP network is a point-to-point packet delivery based on address [85]. Packet is carried from source address to destination address through network similar to delivery system on real world. On the other hand, NDN aims to switch from the notion "where" of content to "what" by carries packet only by name of desired content, intermediate forwarders freely choose among various way to move packet toward to the content provider. Since NDN does not require the name resolution process in IP network, its effectiveness is larger than that of IP based ad hoc network because IP based ad hoc network has no way to access content position in the network. Then, the user does not access content in the ad hoc network.

Based on these considerations, NDN shows advantages over IP-based network that able to adapt to the real network and shows better performance than IP legacy network on where NDN was simulated for palapa-ring and higher education networks in Indonesia [86] [87]. NDN also shows better result on aspect of in-network caching compares to previous network architecture [88].

However, NDN model still have several problems of routing scalability. The scalability of NDN-based routing is affected when increasing the number of network size. There are three main factors that effects NDN scalability: naming efficiency, the scale of routing table and the routing overhead.

Naming: Name on NDN is a hierarchical that represents network hierarchy structure and has no rule or limitation that much more complex than IP. Naming on NDN provides a readable clear-text strings that similar to the Uniform Resource Identifier (URI) or file system scheme, it is unique to assign to each content. The concept of naming helps network can know clearly the content however the length of URI effects the routing/forwarding performance [89].

Routing/forwarding process: Routing process is established first to find the path to content provider, the best path will be chosen to forward the message. For instance, on proactive-based protocol e.g. NSLR [90], node has to maintain its neighbors periodically by sending Hello packet to connected node and wait the reply (Handshaking process), after that LSA packet includes network path map and content is exchanged to create a list of all possible paths. This routing/forwarding process varied by protocol and costs delay of packet process.

Packet overhead: THe network topology changed (the path is broken when node out of transmission) leads to the number of re-transmission packets increases. In case FIB entry is not correct, the packet delivery will be interrupted and more packet to recover the route are required that causes packet overhead. This problem basically existed on IP-based but still a challenge on NDN network [91] [92].

2.3 Applying NDN in Mobile Wireless Ad hoc Network

Routing process on NDN is the way how to construct FIB table based on gathered name-prefix information among nodes. On the other hand, forwarding is the way node delivers Interest/Data hop-by-hop based on each node's forwarding strategy. In the same way with IP-routing-based, routing method in NDN also have flooding, proactive and reactive approaches. The forwarding plane looks up routing information in PIT and FIB table to decide the way to process Interest/Data .

2.3.1 Robust and Efficient Multipath Interest Forwarding for NDN-based MANETs (REMIF)

The first work presents the idea of combining NDN with Wireless Ad hoc network called Robust and Efficient Multipath Interest Forwarding for NDN-based MANETs (REMIF) [11].

REMIF focuses on limited-resources aspect of mobile node. REMIF's idea is simply utilizing only Interest and Data message and does not maintain routing information to mitigate the unnecessary message.

NDN nodes do not use FIB due to the cost of extra packet to update FIB table and additional overhead in network overall. Instead, REMIF forwards packet in a broadcast way and floods the Interest into network to find out the Producer. Furthermore, In order to avoid a broadcast storm problem, REMIF adopts differed timer-based re-broadcasting with remaining energy checking.

2.3.2 Neighborhood-Aware Interest Forwarding (NAIF)

NAIF [12] is a neighbor-aware protocol that aim to reduce the flooding overhead due to mobility and redundant data propagation. Due to all the transmission is broadcast and the senders are hidden from each others leads to collision and congestion, NAIF control the transmission based on adjusting forwarding rate on each node. Forwarding rate is a factor to evaluate that relay node should rebroadcast or drop the received packet. The idea of forwarding rate is node lowers forwarding rate when hears the Data corresponding to the Interest that it already dropped. On the other hand, node also increases its forwarding rate when node realize that it dropped too many Interest.

On first phase, only eligible node which has high data retrieval rate and best distance metric able to participate. Besides that, the ineligible node discard the incoming Interest locally to reduce broadcast storm. The forwarding statistic which based on two factors forwarding rate and data retrieval rate is updated frequently on each node by monitoring the Interest/Data transmitted by itself and overhearing from one-hop neighbor.

On the second phase, the previous eligible node drops arrival Interest probabilistically based on fresh updated forwarding statistics.

2.3.3 Listen first broadcast later (LFBL) [13]

LFBL is originally designed for common multihop wireless network with data centric approach. Although LFBL does not uses any structures of NDN such as Interest, Data, PIT, FIB, LFBL has two phase to retrieve content are request phase and data phase corresponds to flooding phase and second phase of NDN. Furthermore, LFBL uses only one table named Distance Table (DT) acts as a Traditional Routing Table to maintain next-hop identifier for routing process.

On request phase, node broadcasts a packet named Request (REQ) similar to Interest packet to request the Data in NDN manner, this REQ is flooded into network to discover all the content holder. Upon receiving the REQ, intermediate nodes stores the identifier of the sender into its DT, DT can be updated by overhearing a packet being transmitted(Learn from listening).

Once a content holder receives the REQ, it returns a Response packet (REP) used as a Data packet to the requester. REP contains the distance of requester to responder.

2.3.4 Topology aware Content-Centric Networking for Mobile Ad Hoc Networks (TOP-CCN)

The basic concept of TOP-CCN is based on Optimized Link State Routing (OSLR) [12] of IP-based network that aim to control the re-broadcast packets and enhances the stability of content delivery on MANETs. There are two major factors on design:

- Proactive MANET routing approach
- Using three novel algorithms: Multiple Point Relay (MPR), Publisher MPR (PMPR) and flooding range control (FRC)

Different from the standard NDN architecture, TOP-CCN uses three types of packets: Content data packet, Interest packet (new fields added) and the new Content announcement (CA) packet. According to proactive approach, TOP-CCN node 1-hop rebroadcasts periodic CA packet, CA includes prefix information and ID of itself and neighbors. Besides of prefix information, received CA packet node also can obtain the information of neighbor IDs which be used to define two new tables for maintaining one-hop (sender of CA) and two-hop neighbors (neighbors of sender). Additionally, neighbors entries have lifetime and will be removed when expired. In other words, node have more information of global network(prefix and one/two-hop neighbors) for routing decision.

The idea of Multiple Point Relay (MPR), Publisher MPR (PMPR) is based on Multipoint Relays (MPRs) of OLSR. Concept of MPR on OLSR is minimizing the numbers of packet on network by selecting a group of nodes which broadcast the relayed messages. A MPR is selected among one-hop neighbors that can cover all the two-hop neighbors. MPR nodes are allowed to relay all the broadcast packet on network. Among MPR nodes, a PMPR is selected as a node could cover the most number of neighbor nodes. PMPR can generate multi-hop CA packet to disseminate routing information for father away nodes. Figure 2.13 and Figure 2.14 show examples of MPR and PMRP selection.

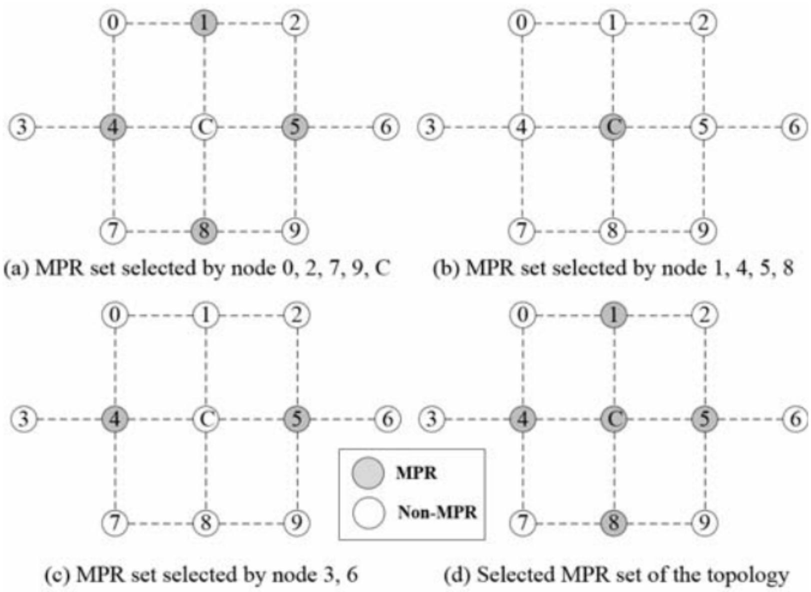


FIGURE 2.13: An example of MPR selection.

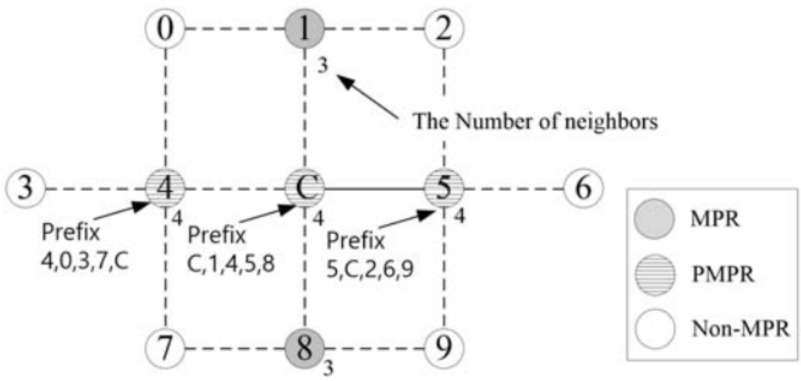


FIGURE 2.14: An example of PMPR selection.

Flooding range control (FRC): Due to the mobility of mobile nodes, traffic for maintaining will increase and cause packet loss or extra delay. Hence, there are some doubts about the accuracy of FIB, PIT information. FRC is designed to control the flooding by estimating the hop-count between sources and destination. Once receives multi-hop CA from PMPR, node measures the expected hop to every node and update them to FIB table. Interest message will be discarded if its expected hop count is lower than the relay node.

2.3.5 Reliable Forwarding Strategy (RFS)

Reliable Forwarding Strategy (RFS) in [33] is similar to Greedy Perimeter Stateless Routing (GPSR) [47]. RFS has a typical neighbor aware forwarding approach which uses the beacon message to maintain neighbor list periodically. Beacon message contains Node ID, Position, Velocity, etc. to be used to determine the metric for each node. Furthermore, RFS considers the direction of moving node as an element to predict and evaluate the links of neighbor nodes.

On Forwarding Interest, node calculates the best metric neighbor as the next relay node. RFS is lightweight protocol that node tries to send Interest as soon as possible before the next beacon reception, it also overhear the network in broadcast nature to make decision to send packet intermediately or wait.

This hop-by-hop process repeats until Interest arrives to Producer. RFS uses PIT to return Data but do not maintain FIB due to the mobility of wireless network that costs amount of traffic pushed into network.

2.3.6 Hybrid Forwarding Strategy Using NDN in VANETs (HVNDN)

HVNDN [34] is a probabilistic and opportunistic protocol that focusing on the reliability of transmission. The information in HVNDN is based on their location dependence and location independence characteristic, forwarding strategy varies to each category. HVNDN implements forwarding process under NDN architecture and also take advantages of geographic approach forwarding to improve the efficiency, reliability of the communication.

HVNDN node utilizes two types of message: Interest and Data. In addition, HVNDN defines new two types of Interest called Location Dependence Interest (L-Int) for location dependence information and Blind Interest (B-Int) for location independence information.

L-Int is an Interest includes the ID and location of Producer. This kind of information is used when the Producer has a location can be seen on the map such as Gas station, restaurant, parking area etc. Once a Consumer wants to request a content, it broadcasts a L-Int contains the destination coordinates of the Producer, thus HVNDN node replaces FIB based forwarding by a location-based forwarding. The intermediate nodes works based on receiver-oriented manner that discard this Interest if its position to the Producer is father than the original Consumer, otherwise it processes this incoming Interest following the flow of NDN processing, if no matching PIT entry or cache was found, node generates a delay timer and re-broadcasts the Interest. Furthermore, HVNDN uses re-transmission and acknowledgement mechanism to provide a packet reliability by re-sending the Interest if acknowledgement not arrives on time of delay timer. Data is forwarded reversely by PIT entries. In addition, node avoids the waste of bandwidth by broadcasting Data with acknowledgement to valid to inform running around vehicles to cancel duplicated Data message forwarding.

On the other hand, Consumer has no clue about location of the Producer, node broadcasts the B-Int in a flat-forwarding manner (no direction information) based on a probability. This probability is defined on the parameters of relay node such as velocity or transmission range. Due to the "blind" characteristic of this scenario, the path can be broken in anytime, node in HVNDN uses acknowledgements to maintain the link. If the broken link was found during returning Data way, the intermediate nodes that attended to Interest forwarding way will re-transmit the Interest. The changes of topology makes amount of unnecessary re-transmit message problem occurs.

2.3.7 Last Encounter Content Routing (LER)

LER [35] is an opportunistic geo-cast based routing method where node maintains and updates the content holder position using last encounter information. LER focuses only on location independent scenario to solve the current limitation of HVNDN. LER has the characteristics of a reactive protocol which has three main processes: request, reply and maintain.

Node in LER maintains two tables: Content List and Last Encounter List (LEL). Table 2.3 shows the structure of LEL contains the name prefix, ID of Producer, the last met location and time as shown . Instead of using FIB, LER utilizes this LEL to implement a geo-cast based forwarding. Similar to beacon message, node exchanges the Content List to populate the relative information of content among one-hop neighbors. Once receiving the Content List, node synchronize this information with its LEL, node keep updating its LEL if they have newer information, due to the caching there are many content holder for one content that leads multi-path forwarding can be applied.

TABLE 2.3: The format of Last Encounter List (LEL).

Content Name	**Vehicle ID**	**Location**	**Time**
test.doc	B	(y,z)	11:20am

In the same way of NDN based method, node broadcasts the Interest to discover the location of content on first phase if matching LEL entry was not found. Once the Interest arrives an intermediate node that stores LEL entry correspond to desired content. Node actives the broadcast to geo-cast switching mechanism on second phase by adding location information of content into Interest message to send out by opportunistic geo-cast. Similar to the beacon-based methods, the drawback of LER is overhead of Content List message, furthermore unnecessary content has to stored and updated costs redundant resources of network.

2.3.8 A multi-hop and multi-path routing protocol using NDN for VANETs (MMM-VNDN)

A Multi-hop and Multi-path Routing (MMM-VNDN) [36] is a solution to deal with original NDN problem of lacking node identification and introduces a new protocol by utilizing MAC address of nodes. MMM-VNDN aim to recover V-NDN, makes this protocol works correctly under the architecture of NDN which originally supports for Wired Network. The duplicated face problem which mentioned above was solved by using MAC address instead of Face.

MMM-VNDN has two main ideas are replacing Face by MAC address and broadcast-to-unicast switching mechanism. MAC address is added into Interest, Data to provide a multi-hop, multi-path routing protocol and allows vehicles to transmit and receive message simultaneously. MMM-VNDN also proposes a next-hop selection mechanism based on the latency of network connection.

The rest of MMM-VNDN works like wired-NDN when the Consumer floods the first Interest to discover content, intermediate nodes update PIT and FIB and forward the Interest until arrives Producer. Data return by PIT and Consumer sends the following Interest with same content in unicast by using FIB table.

Although MMM-VNDN is a full-function protocol that applying NDN in Vehicular Networks, it has some limitations that is not suitable for VANETs. The critical point is lacking of a real-time updating mechanism once topology changes, in MMM-VNDN node has to rebuild FIB by returning to flooding Interest phase, it costs delay and traffic of entire network.

2.3.9 Summary of routing protocols in NDN based Wireless Ad Hoc Network

Routing protocols in NDN based Wireless Ad Hoc Network are summarized comprehensively in Table 2.4.

For the RQ1 on MANETs scenario, although almost previous methods are receiver-based approach that reduce the number of node able to rebroadcast the packet by selecting eligible forwarders (NAIF, LFBL) or reducing the number of packets by setting a delay timer (REMIF), however they are almost do not use FIB table that not able to support unicast-communication that causes redundant flooding packet (Control packet, Interest and Data) and lack of prefix management for the large scale of network.

On VANETs scenario beacon-based method is the most common where node maintains its neighbors periodically and forward the packet to candidate node directly that FIB is not be used. The limitation of beacon-based approach is easily damaged by the inaccuracy (wrong direction forwarding) or out-dated beacon (node unreachable forwarding) leads to packet loss that more frequently occurs than MANETs because of high mobility of vehicle. In contrast, beacon-less method does not maintain the neighbor nodes, the forwarding decision is FIB-based (MMM-VNDN) or geographical-based (HVNDN). In vehicular network, due to the movement of node is predictable, MMM-VNDN is suffered by flat-forwarding problem (forward packet to any directions). Furthermore, the concept of the producer came from anywhere, HVNDN's location independent is still blind forwarding that not supports for such kind of scenario effectively.

In addition, Besides MMM-VNDN that provide a solution to dealing the issue of FACE logic in NDN by using MAC address replaces FACE, almost previous methods are do not support or not be explained on detail about the problems which we mentioned on RQ2.

TABLE 2.4: Routing protocols in NDN based Wireless Ad Hoc Network .

Routing Protocol	**Type**	**Description**	**Limitation**
REMIF [11]	Reactive	REMIF adopts differed timer-based with remaining energy checking before rebroadcast to reduce flooding.	Broadcast storm due to not maintaining FIB.
NAIF [12]	Reactive	Monitoring forwarding statistics by overhear transmitted packet by itself and one-hop neighbor. Only eligible node able to participate the communication to reduce broadcast storm.	All broadcast communication.
LFBL [13]	Reactive	Use REQ, REP similar NDN packets, intermediate nodes rebroadcast and overhear broadcast packet to update Distance Table for unicast on second phase.	All broadcast communication.
TOP-CCN [32]	Proactive	Periodic broadcast control packet to maintain 1-hop and 2-hop neighbor, only selective nodes can rebroadcast to reduce traffic overhead.	Control packet overhead, not suitable for large scale network.
RFS [33]	Beacon	Periodic maintain neighbors by beacon, select best next-hop based on metric and return Data by PIT.	No prefix management, packet loss due to the out-of-date beacon.
HVNDN [34]	Beaconless	Has two strategies for location independent and location dependent information.	High latency and overhead due to acknowledgement function on location-dependent. Blind-forwarding on location-independent
LER [35]	Beacon	Maintain and update the content holder position using last encounter information, do not maintain FIB that on second phase broadcast to geo-cast switching.	Control packet overhead and unnecessary content is cached.
MMM-VNDN [36]	Beaconless	Fully NDN function with broadcast-to-unicast switch mechanism on second phase and use MAC Address to replace FACE.	Flat forwarding due to not using position information.

Chapter 3

Hybrid NDN based Ad hoc Routing combining Proactive and Reactive mechanisms

3.1 Introduction

In This Chapter, we proposed a new NDN based ad hoc routing for MANETs to answer the RQ1 and RQ2. Our proposal has the following three features.

First, due to the single face communication mentioned on RQ2, we switch the next-hop object in our design from Face into MAC address to exploit the FIB and PIT for routing decision.

Second, our proposal originally focuses on supporting the typical ad hoc network for local-area content dissemination of public spaces such as shopping mall, museum, park or library etc. For the long-live content such as guidance, map or area-based announcement, we can pre-configure the content to reduce the routing cost. However, customers or visitors come and leave this area frequently and normally also request the short-live content such as restaurant table availability, finding parking place or latest information of specific area that be missed before arrival and required daily-updated (New opening shop, new event or flash sale information). Thus, based on the specification of content, a proactive-based protocol for the Producer side which has a stable network where producers and intermediate routers are located in fixed positions is required to improve the flexibility of maintaining such dynamic content.

On the other hand, the mobility nodes move in and out more frequently and has only one role requesting the desired content. Therefore, we consider that a hybrid method that able to take advantages of both approaches is required. Previously, In the IP based ad hoc network, a hybrid routing is also proposed [43] but the approach of our hybrid design is combining previous existed NDN-based proactive and reactive protocols, not the way of implementing NDN on current hybrid MANET protocol. Thus, our Hybrid MANET protocol normally adopts the benefit of NDN architecture compares to traditional ad-hoc network about in-network caching, on-demand pull-based forwarding and multi-provider that much more suitable to the dynamic topology of wireless network. Based on these considerations, we take a hybrid approach that the proactive routing is adopted in a producer side network, because of its in-advance route setting, and the reactive routing is adopted in a consumer side network, because of its flexibility for mobility.

The third feature is about the procedure of proactive routing. The NDN proactive routing procedures proposed so far are advertising both the network topology and the name prefixes. However, the point of NDN routing is how the name prefixes are disseminated. In order to realize this requirement, it is sufficient that the shortest path information is maintained for individual producer. So, we proposes a new proactive NDN routing focusing on just the name prefix advertisement.

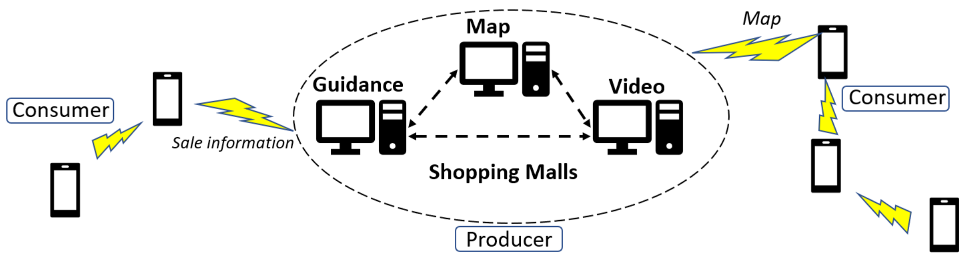


FIGURE 3.1: Hybrid approach for local-area content dissemination

The rest of the Chapter is organized as follows: Section 3.2 proposes our new protocol. Section 3.3.3shows the results of performance evaluation by 2 methods: Theoretical analysis and real experiment by using NDNsim, we also introduce a detail of implementing NDN architecture to wireless network. Section 3.5 concludes this chapter.

3.2 Design Principles

We have adopted the following design principles for our hybrid NDN based routing mechanism as shown in Figure 3.9.

We split the network topology to two parts: Producer and consumer side. The Producer side has all the producers and intermediate routers with fixed location characteristic so on this side the link is stable so we offer a proactive based routing. On the other hand, the mobile nodes such as smartphones has limitation of resource and energy instead of maintaining the route, consumer side provide a reactive-based routing where route is generated on demand.

For the producer side, our proactive routing focuses only on the name prefix advertisement. It constructs a directed a cyclic graph (DAG) starting from each producer. An FIB entry for a specific name prefix is given by pointing upstream nodes so as to traverse the corresponding DAG in a reverse direction. If there are more than one upstream nodes, all of them are registered in the entry and used for multipath forwarding [37].

In order to create a DAG for a specific name prefix, the corresponding producer issues a Name Prefix Announcement Request (NPAreq) packet. It is broadcasted, and if any receiving NDN nodes are on the corresponding DAG, they return a Name Prefix Announcement Reply (NPArep) packet by unicast.

On consumer side, mobility node on our scenario has the role of a customer that arrives and leaves regularly. Instead, node generate the first Interest to discover the desired content. This first Interest packet is flooded throughout the consumer side, and once it arrives some node belongs to the producer side, the forwarding process switches from broadcast to unicast on this side to forward this Interest to the Producer. Once Interest satisfied Producer was found, the Data will be return to original Consumer and s set of temporary FIB entries were created on nodes of Consumer side simultaneously. The following is Interest of same content can be forwarded by the route which already built by first Interest.

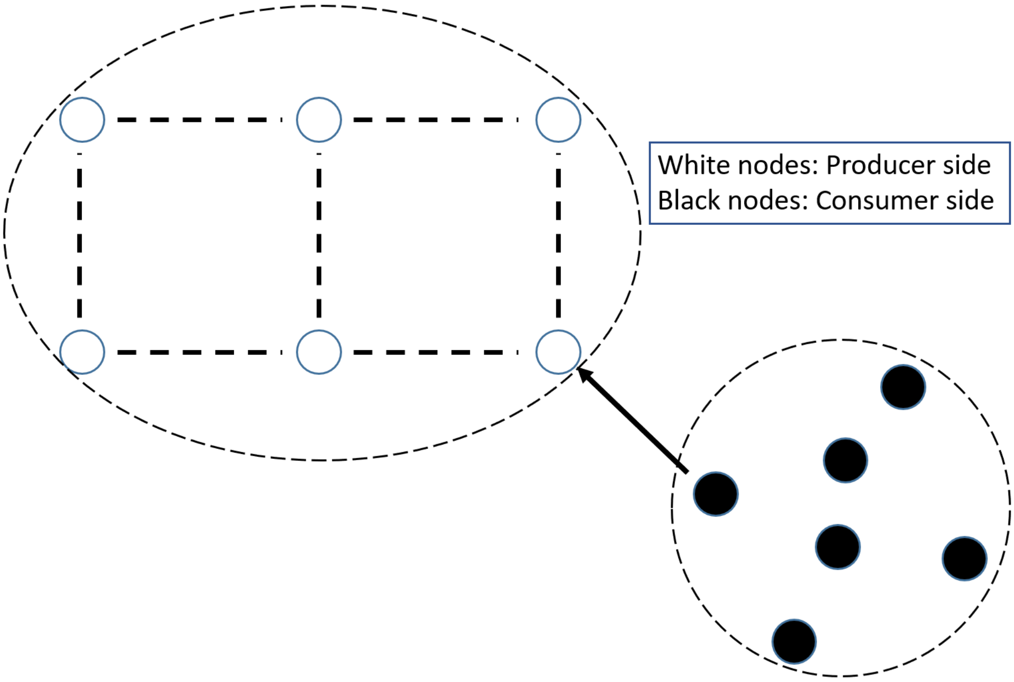


FIGURE 3.2: Dividing network into Consumer side and Producer side.

3.2.1 Face to MAC Address Switching

The current NDN design is originally support for wired network where node have multi-interface to send and receive via incoming-face and outgoing-face separately. However, in wireless environment node commonly has only one WiFi interface makes the incoming-face and outgoing-face of FIB and PIT is undefined for routing process. To deal this problem we introduce a Face to Mac Address switching concept to identify each specific node for unicast-based forwarding purposed which will be explained in details on the performance evaluation section as shown in Figure 3.3.

The aim of this concept is reducing broadcast communication and to implement our protocol on NDNSim simulator correctly. As shown in Figure 3.4 we replace the Face notion of NDN logic on both PIT and FIB table into MAC Address that helps to identify the incoming-face and outgoing-face based on unique Node identifier (The MAC Address of node). Based on the sender and receiver identifier, a hop-by-hop unicast based forwarding process be able to defined. Furthermore, instead of changing the structures of Interest or Data like several previous works, we simply maintain the incoming-face (MAC Address of the sender) via PIT and outgoing-face (MAC address of the receiver) via FIB table by following actions.

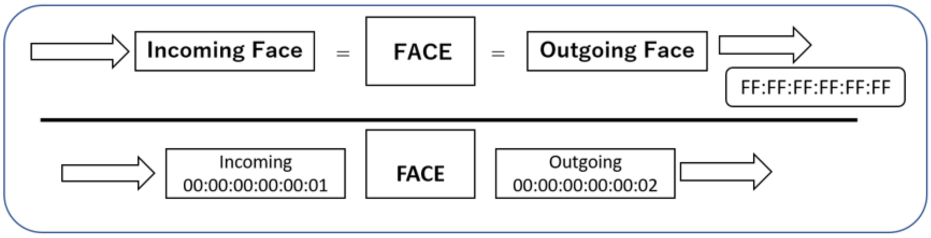


FIGURE 3.3: Face duplication of NDN

Prefix	Incoming Face
test	00:00:00:00:00:01

Mac Address of Sender

Pending Interest Table (PIT)

Prefix	Outgoing Face
test	00:00:00:00:00:02

Mac Address of Receiver

Forwarding Information Base(FIB) Table.

FIGURE 3.4: Switching from Face to Mac Address on PIT and FIB Table.

• For incoming Interest, in order of NDN processing the MAC address of the sender is captured and store in PIT entry's incoming-face field and node continues to look up its FIB table. In case receiver Mac address was found, node puts this MAC address into Face field of Interest and sends this Interest in unicast manner, otherwise this Interest will be sent to broadcast address.

• For incoming Data, node examines its PIT entry, extracts the MAC address of the requester and puts it into Face field of Data to returns.

3.2.2 Producer Side

Table 3.1 shows the parameters contained in NPAreq and NPArep packets. Producer node ID is the MAC address of the producer node, and NPAreq and NPArep packets can be uniquely identified using this ID and nonce assigned by the producer. A producer generates NPAreq packets periodically, which contains the name prefix list that it is publishing. Hop count is the number of hops from the producer which generated this NPAreq packet. When a producer side node receives an NPAreq packet, it rebroadcasts the received packet with incrementing hop count and setting the number of child nodes (nodes located downstream in a DAG), and return an NPArep packet to the sender of the NPAreq packet. The number of child nodes is used for ranking upstream nodes in an FIB entry. The detailed procedure for specifying FIB are described below.

TABLE 3.1: Parameters in NPAreq and NPArep packets.

Packet	Parameters
NPAreq	producer node ID, producer nonce, name prefix, prefix list, hop count, number of child nodes.
NPArep	producer node ID, nonce.

Figure 3.5 shows the structure of FIB used by producer side nodes. The structure is similar with that of the original NDN specified in [38]. An FIB entry is created for individual name prefix, and it may contain multiple forwarding candidates. Each candidate has the forwarding parameters, which include the interface ID, ID of neighbor node (upstream node in a DAG), and other parameters such as RTT. More than one forwarding candidates may be ranked according to some routing policies. In the proposed method, a node with more child nodes (downstream nodes) has higher priority. We selected this policy because the possibility of using Data packet caching will be higher in the node with more downstream nodes.

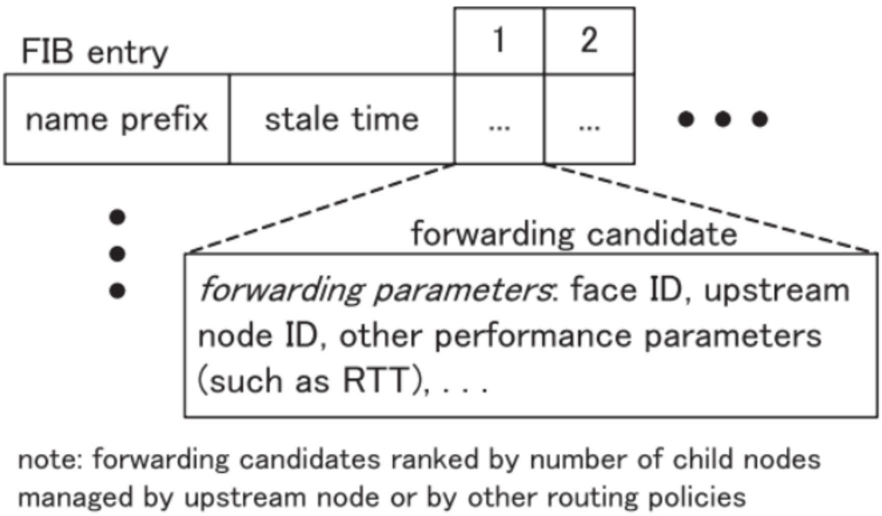


FIGURE 3.5: Structure of FIB at producer side

In order to construct FIB entries, the proposed method maintains the DAG table shown in Figure 3.6. This table maintains the information given in NPAreq packets. An entry corresponds to one name prefix and includes one or more upstream records, each of which includes a list of producer ID, its nonce, hop count from the producer, the face ID and upstream node ID, and the number of sibling nodes and child nodes. These upstream records are ordered according to the hop count from the producer, and if the hop count is the same, according to the number of sibling nodes.

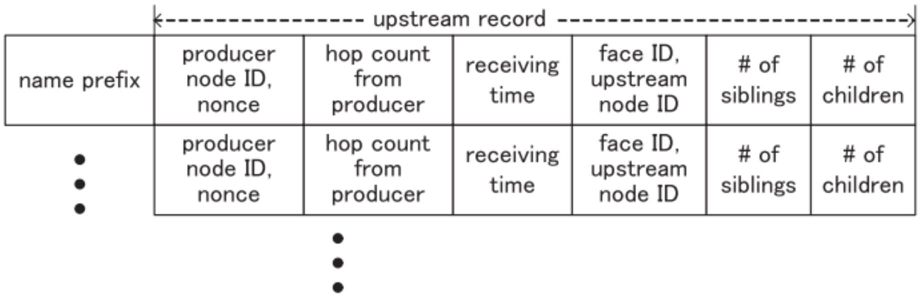


FIGURE 3.6: Structure of DAG table at producer side.

A node receiving an NPAreq packet follows the procedure given below and in Figure 3.7.

1. Check whether there is an FIB table entry for the name prefix specified in the received NPAreq packet.

2. If there are no such entries, add a new FIB entry and a new DAG table entry with the MAC address of the sender of the NPAreq packet set in the upstream node ID. Send an NPArep packet to the NPAreq sender, and rebroadcast the NPAreq packet.

3. Otherwise, check whether there is an upstream record in the corresponding DAG table entry which has the same producer node ID. If there is such an upstream record, then look for records in which the nonce is the same as that in the NPAreq packet.

(3-1) If there are no such records, handle this NPAreq as a new advertisement. That is, delete the upstream record corresponding to the producer node ID and nonce pair in the DAG table entry, and delete if the list becomes empty, delete the forwarding candidate, if there are any in the corresponding FIB entry. After that, add a new forwarding candidate and a new upstream record when necessary. Send an NPArep packet to the NPAreq sender, and rebroadcast the NPAreq packet.

(3-2) Otherwise, that is, when there are some upstream records having the same pair of producer node ID and nonce with the NPAreq packet, compare the hop count in the record with that in the NPAreq.

(3-2-1) If the hop count in the record is smaller, then ignore the received NPAreq packet.

(3-2-2) If two hop counts are the same, then check whether there are any upstream records which have the upstream node ID identical to the NPAreq sender address.

A) If there is such a record, ignore the received NPAreq packet.

B) Otherwise, that is, when the NPAreq is sent by a new upstream node, add a new upstream record in the DAG table entry, and a new forwarding candidate in the FIB entry, and return an NPArep and rebroadcast the NPAreq. This is for multipath forwarding.

(3-2-3) Otherwise, that is, when the hop count in the upstream record is larger than that in NPAreq packet, handle this NPAreq as a new advertisement. Act as in step (3-1).

4. Following the first part of step 3, the last step is for when there are no candidates with the producer node ID specified in the NPAreq packet, that is, when an NPAreq with the same name prefix from a new producer. In this case, compare the hop count in the upstream record with that in the received packet, and act in the same way as (3-2-1) through (3-2-3) according to the result.

In any step where some upstream record is created or modified, the number of downstream nodes managed by upstream node needs to be modified according to the received NPAreq packet.

When a node receives an NPArep packet, it looks for an upstream record with the producer node ID and nonce in the packet, and increments the number of child nodes managed by this node by one.

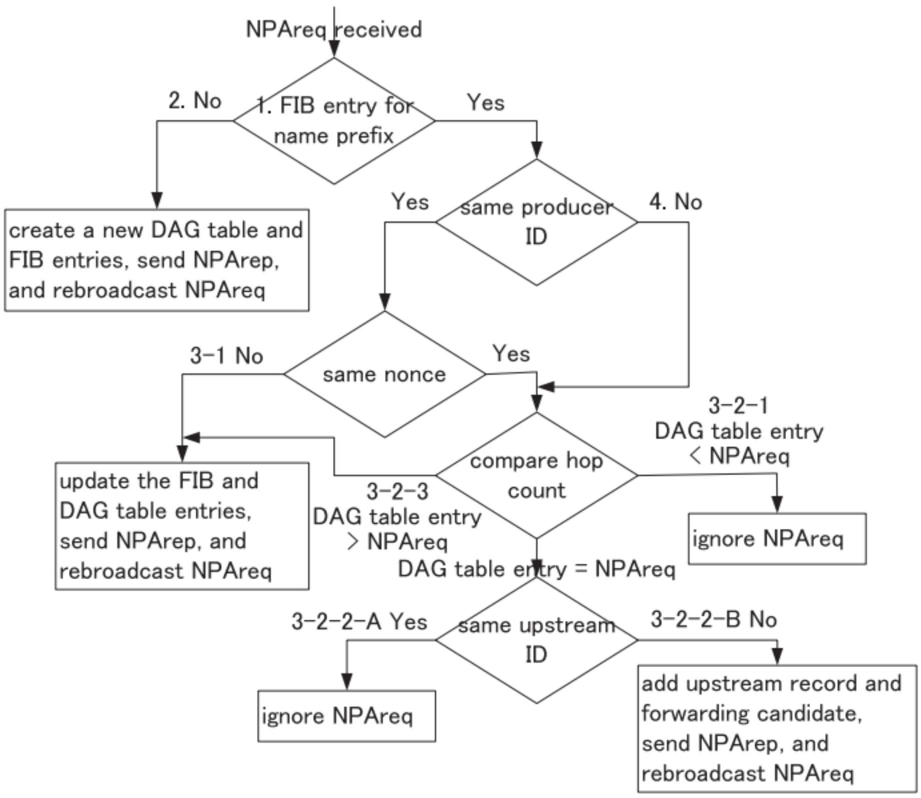


FIGURE 3.7: Flow chart for a received NPAreq packet.

Figure 3.8 shows an example of how this protocol works. As shown in Figure 3.8 (a), there are six producer side nodes connected with wireless links shown in dashed lines. Among them, node 2 is a producer and the others are NDN routers.

As shown in Figure 3.8 (b), in the beginning, node 2 broadcasts an NPAreq packet with producer node ID = 2, nonce1, "name", hop count = 1, and number of downstream nodes = 0. Nodes 1, 2, and 5 receive this packet, create an FIB entry and a DAG table entry as shown in the figure, and return an NPArep packet individually. Then node 5 rebroadcasts the NPAreq packet with changing hop count to 2, and nodes 4 and 6 respond it. Node 2 receives the packet but ignores it. When node 5 receives the NPArep packets from node 4 and 6, the number of child nodes in this node is set to 2.

Next, node 1 rebroadcasts the NPAreq packet, to which node 4 responds. As a result, the FIB entry and the DAG table entry in node 4 have two forwarding candidates and two upstream records to node 1 and 5. Similarly, the NPAreq packet rebroadcasted by node 3 is handled by node 6. In the end of this advertisement, the NPAreq packets are rebroadcasted by nodes 4 and 6, but nobody responds to them. The generated DAG is shown in Figure 3.8 (c).

After some periods, node 2 broadcasts a new NPAreq packet with nonce2. After this new NPAreq packet is disseminated, the FIBs and the DAG tables of individual nodes are set as shown in the figure. It should be noted that the FIBs in nodes 4 and 6 have two forwarding candidates with node 5 and nodes 1/3 as upstream nodes, respectively. These candidates are ranked by the number of downstream nodes managed by upstream node. Since node 5 has two child nodes, the forwarding candidate to node 5 is ranked first.

So far in this subsection, we do not mention PIT in producer side nodes. The PIT structure in producer side nodes is identical to that used in original NDN nodes [37], except that the interface ID is replaced by the pair of the interface ID and the neighbor node ID (MAC address). This will be discussed in the next section.

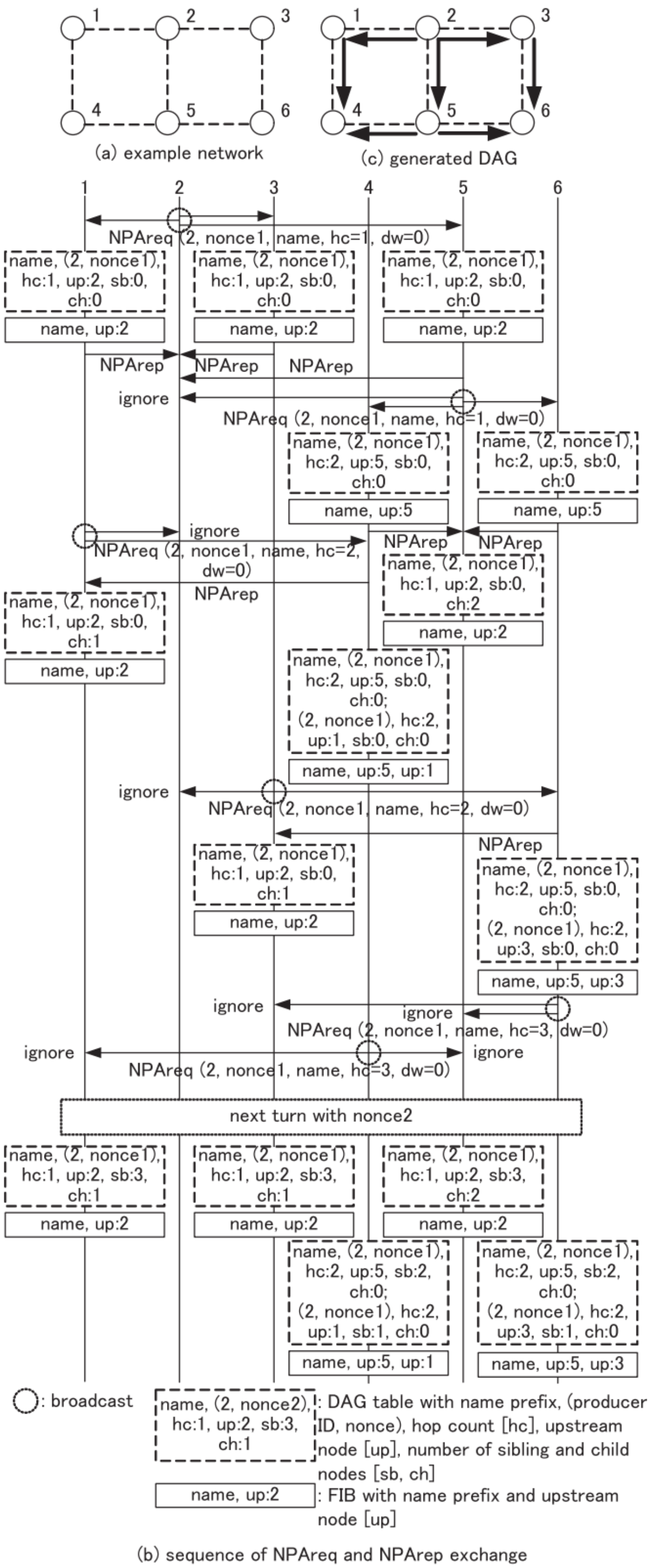


FIGURE 3.8: Communication sequence at producer side

3.2.3 Consumer Side

As described above, the NDN nodes in the consumer side network are mobile terminals, which move around. So, we introduce a reactive routing mechanism in the following way.

First of all, FIB is not set in the consumer side beforehand. When a node starts to retrieve a specific content, the first Interest packet for the content is flooded among consumer side nodes. When an Interest packet reaches some producer side node, it will be transferred to the corresponding producer. The producer sends back the Data packet containing the requested content. It is transferred through the reverse path of the Interest packet. When it goes through the consumer side nodes, FIB entry is set in individual nodes. The following Interest packets accessing to this name prefix use the FIB arranged. For the consumer side, we use the original formats of Interest and Data packets and the original structures of FIB and PIT, except that the first Interest packet is broadcasted and that a neighbor node MAC address is used as an interface ID.

Figure 3.9 shows an example of the communication sequence between a mobile consumer and a producer. As shown in Fig. 5 (a), the producer side nodes are the same as in Figure 3.8 (a), and there are three consumer side nodes (nodes p, q, r). The dotted line shows a wireless link.

We assume that the FIBs are arranged in the producer side nodes. As shown in Figure 3.9 (b), node p starts contest retrieval for name prefix “name” and the first Interest is for “name/001”. The Interest packet is broadcasted and nodes q and r receive it. Then node q rebroadcasts the Interest packet, and nodes 6 and p receive it. Node p ignores this Interest, because it is a duplicate one. Node 6 relays the received Interest packet to node 5 according to its FIB. On the other hand, node r also rebroadcasts the Interest packet, which nodes 6 and p receive. But both nodes ignore this Interest because of the duplication.

The Interest packet is sent to node 2, producer, via node 5, and in response to it, the Data packet containing the content of “name/001” is returned along the reverse path of the Interest packet. That is, the Data packet goes via nodes 5, 6, and q, and reaches node p. When node q relays the Data packet, it creates an FIB entry for “name” which indicates that the upstream node is node 6. Similarly, when node p, consumer, receives this Data packet, it creates an FIB entry for “name” indicating that the upstream node is node q. For the following Interest packets, nodes p and q use the created FIB. That is, the next Interest packet requesting content for “name/002” is sent to node q in the unicast communication. Similarly, node q relays this Interest to node 6 directly.

When some nodes move and the communication link is broken, the Data packet is not returned and the timer for Interest packet will be expired. At that time, node p, consumer, will broadcast the lost Interest packet, and the similar procedure with the first Interest is performed.

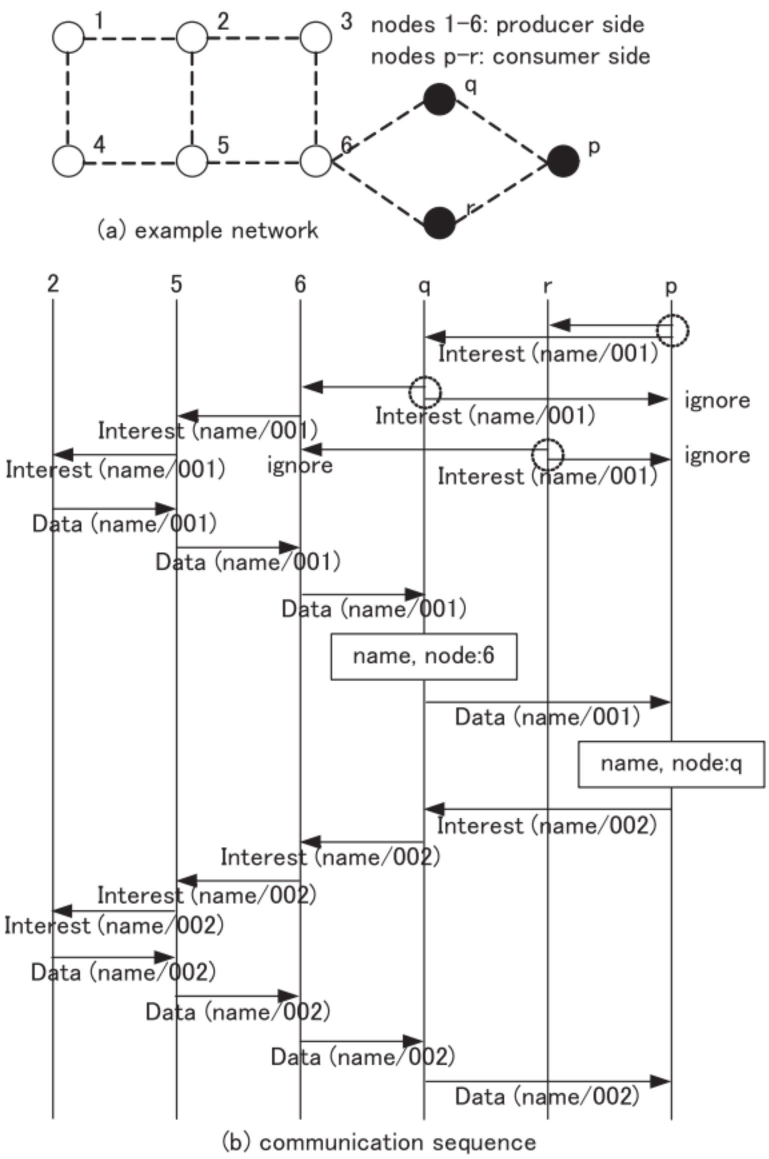


FIGURE 3.9: Commmunication sequence between consumer and producer

3.3 Performance Evaluation

3.3.1 Theoretical analysis with fixed node configuration

This section describes the results of performance evaluation using a configuration where the node position is fixed. The evaluation focuses on the overhead of routing control and Interest packet transfer. We compare our proposal, TOP-CCN as an example of proactive mechanism, and REMIF as an example of reactive mechanism.

Experiment configuration

Figure 3.10 shows the network configuration used in this evaluation. Nodes are arranged in a grid network, n nodes in the horizontal direction and 4 nodes in the vertical direction. Similarly with the examples above, the dashed line is a wireless link.

Figure 3.10 (a) shows the detailed configuration for our proposal. The first and second rows are the producer side, and the third and fourth rows are the consumer side. Figure 3.10 (b) shows the detailed configuration for TOP-CCN. According to [32], the light gray nodes are PMPRs and the dark gray nodes are MPRs. In REMIF, all nodes are handled equally. We assume that some nodes in the first row work as producers. That is, the number of producers change from 1 to n. We also assume that consumers locate in the third and fourth rows. In the evaluation, one consumer communicates with one producer for independent content. So, the cache is not effective in this evaluation.

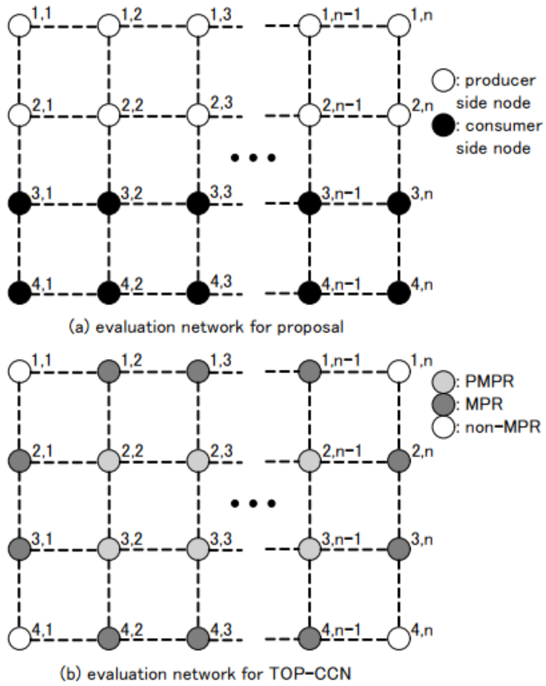


FIGURE 3.10: Evaluation network for proposal and TOP-CCN

Results of routing control overhead

Since our proposal and TOP-CCN use a proactive routing mechanism, they have some overheads in routing control. Routing control is performed periodically, but in this evaluation, we calculate the total number of control packets exchanged in one turn. We suppose there are *m* producers.

(1) Our Proposal

The details for our proposal are as follows. First, we consider the case that there is one producer (a node among 1,1 through 1,n). The producer issues an NPAreq packet, and it is rebroadcasted by any other nodes in the first and second rows, once per node. So, the total number of broadcasted NPAreq packets is *2n*. As a result of routing control, a rudder style network is generated as a DAG (see Figure 3.8 (c)). In order to generate this configuration, one NPArep packet is transferred once over one wireless link. Therefore, the total number of transmitted NPArep packets is equal to the number of wireless links, that is, *3n-2*. So, the routing overhead for one producer is *5n-2* in our proposal. For the case of *m* producers, the total number becomes *m* times as the case of one producer. Therefore, the result is *m(5n-2)*.

(2) TOP-CCN

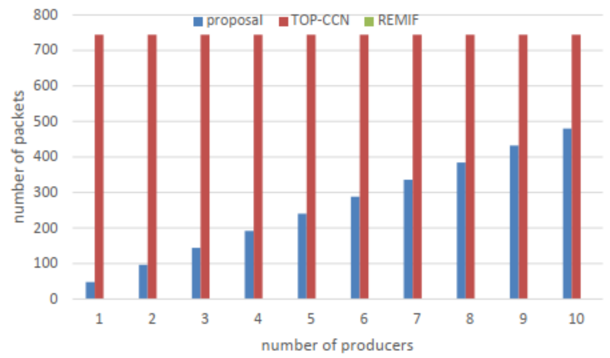
In the case of TOP-CCN, the number of control packets does not depend on the number of producers. The details for TOP-CCN are as follows. For non-MPR nodes (white nodes in Figure 3.10 (b)), one CA packet is sent for advertising itself, and another CA packet is sent for MPR selection. So, the number of CA packets is 2 per node. For MPR nodes, a CA packet is sent for one neighbor detection, and the number of neighbors is 3. One CA packet is sent for MPR selection. For route announcement, it sends CA packets as many as the number of PMPR. Therefore, the number of CA packets is 4 + number of PMPR per node. For PMPR nodes, one CA packet is sent after one neighbor detection (there are four neighbors), and one for MPR selection. For relaying multi-hop CA packets, the number of CA packet transfer is equal to the number of PMPR nodes. Therefore, the total number is 5 + number of PMPR per node. The number of MPR and PMPR is *2n* and *2(n - 2)* , respectively. As a result, the total number is

$$2 \times 4 + 2n(4 + 2(n-2)) + 2(n-2)(5 + 2(n-2)) = 8n^2 - 6n + 4$$

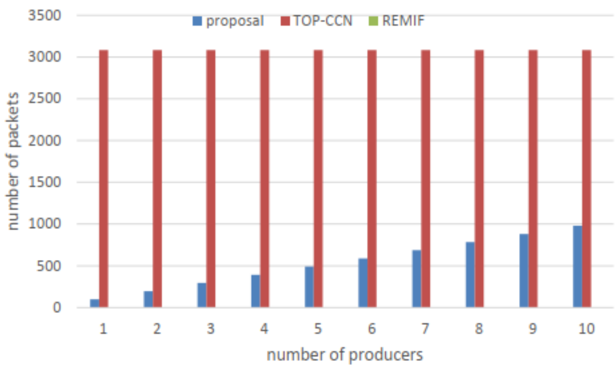
(3) Results

Figure 3.11 shows the number of routing control packets when n is 10 and 20, by changing the number of producers (m) from 1 to 10. When n is 10, the results are summarized in the following way (see Figure 3.11 (a)). In our proposal, the number of NPAreq and NPArep packets changes from 48 to 480 when m changes from 1 to 10. On the other hand, in TOP-CCN, the number of CA packets is always 744 independently of m. In REMIF, there are no routing control packets.

When the number of nodes in the horizontal axis becomes twice, as shown in Figure 3.11 (b), the situation changes as follows. The number of CA packets in TOP-CCN increases from 744 to 3,084. On the other hand, the number of control packets in our proposal changes from 98 to 980 in response to the increase of m. The number of CA packets in TOP-CCN has a larger increase compared with that of our case. This is because the CA packet number depends on the order of n^2. In this sense, our proposal is effective in terms of the routing control overhead for the node number increase.



(a) n=10



(b) n=20

FIGURE 3.11: Number of routing control packets

Results of Interest transfer overhead

In spite of the weakness in routing control overheads, the proactive mechanism provides more efficient Interest packet transfer then the reactive mechanism. Here, we suppose that there are one hundred Interest packets for one specific name prefix, and count the total number of Interest packets transmitted over wireless links (total Interest hop count). The calculation is done by changing the number of consumer and producer pairs from 1 to n.

(1) Our Proposal

In the case of our proposal, only the first Interest packet is flooded among consumer side nodes and producer side nodes except the producer itself. So, the total Interest hop count (average) for our proposal is

$$(4n-1)m + 99m(\frac{5}{2} + \frac{n^2-1}{3n})$$

For 100 Interests with m consumer / producer pairs, the total Interest hop count (average) for TOP-CCN is

$$100m(\frac{5}{2} + \frac{n^2-1}{3n})$$

(2) TOP-CCN

In the case of TOP-CCN, the optimum route is used for all Interest packets. When there is one consumer / producer pair, the average hop count of one Interest packet is obtained in the following formula. Please remember that a producer is located in the first row, and a consumer is located in the third or fourth row. The first item is an average vertical hop and the second is for horizontal transfer.

$$\frac{5}{2} + \frac{\sum_{j=1}^{n} \sum_{i=1}^{n} |i-j|}{n^2} = \frac{5}{2} + \frac{n^2-1}{3n}$$

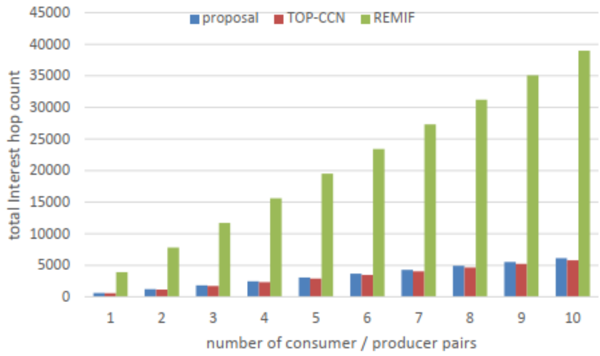
(3) REMIF

In the case of REMIF, since there is no FIB, every Interest packet is flooded. In the grid configuration used here, every node except the producer will rebroadcast each Interest once. So, the result is

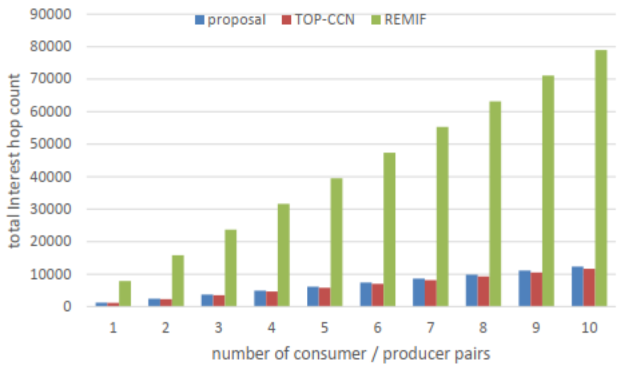
$$100(4n-1)m$$

(4) Results

Figure 3.12 shows the total Interest hop count (average) when n is 10 and 20, by changing the number of consumer /producer pairs (m) from 1 to 10. This figure indicates that the total number of REMIF is much larger than the others. The result of our proposal slightly higher than TOP-CCN. By comparing Figure 3.12 (a) and Figure 3.12 (b). the tendency is similar for two cases that n is 10 and 20. This is because the number of transmitted Interest packet changes in the order of n for three methods.



(a) n=10



(b) n=20

FIGURE 3.12: Total Interest hop count (average)

3.3.2 Theoretical analysis with moving node configuration

In this section, we show the performance evaluation when one of the consumer side nodes moves around.

Experiment configuration

We use a network configuration as shown in Figure 3.13, which consists of thirty one nodes; thirty nodes are fixed, and one is moving from the left side end to the right side end. We assume that the distance between adjacent nodes is 10 meter and the speed of the moving node is 1 meter/sec. In this experiment, the moving node (node 4) is only the consumer that originates Interest packets, and the node located at the upper right position (node 1,1) is the producer

In the case of our proposal, as shown in Figure 3.13 (a), twenty nodes (1,1 through 2,10) work as producer side nodes, and eleven nodes (3,1 through 3,10 and 4) are consumer side nodes.

In TOP-CCN, the assignment of PMPR and MPR is given in Figure 3.13 (b) and Figure 3.13 (c). When the moving node is communicating with the left end node in the third row (node 3,1), this node works as an MPR and its next node (node 3,2) is a PMPR (see Figure 3.13 (b)). The situation is similar when node 4 communicates with node 3,10. In other cases, as shown in Figure 3.13 (c), nodes 3,1 and 3,10 are non-MPRs, and the other nodes in the third row are MPRs. In the case of REMIF, all nodes work in the same way, which is similar with the evaluation in the previous section.

We assume that node 4 sends Interest packet once per 100 msec, that is, the Interest sending rate is 10 packets/sec. In the cases of our proposal and TOP-CCN, we assume that the initial routing setting is done just before node 4 starts moving. We also assume the following route maintenance in our proposal and TOP-CCN. In our proposal, the route establish procedure, i.e. the exchange of the NPAreq and NPArep packets are performed once per 10 seconds among the producer side nodes. In TOP-CCN, CA packets are sent periodically, once in one second by each node, to detect the change of network configuration, and if any route happens, CA packets are flooded that carry the changed neighborhood information.

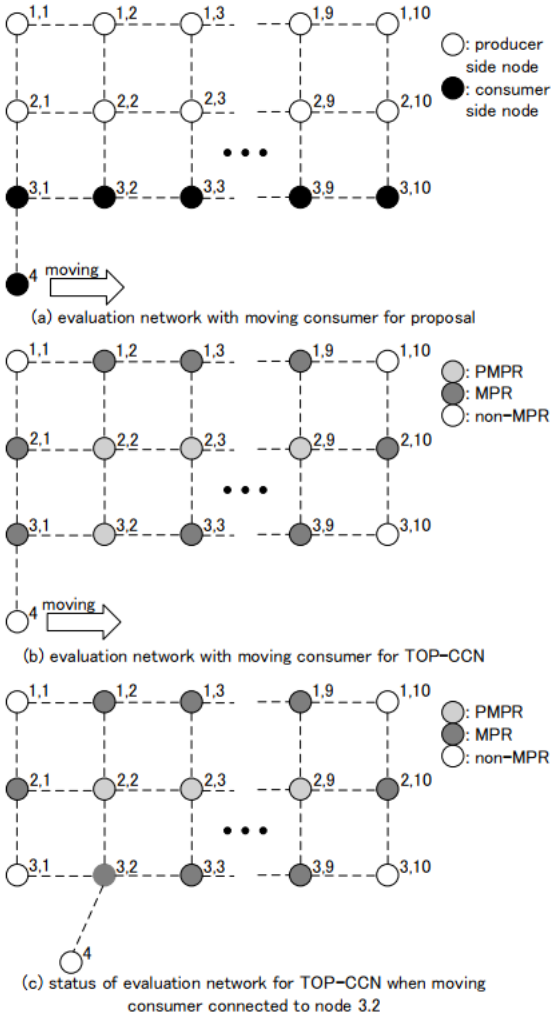


FIGURE 3.13: Evaluation network with moving consumer for proposal and TOP-CCN

Number of transmitted packets

Here, we analyze the time variation of the number of transmitted packets. The number of transmitted packets means the total hops of all packets used in the individual methods; control packets, Interest packets and Data packets.

(1) Our Proposal

In the case of our proposal, the route setting is done at the beginning. The number of packets is obtained in the same as VI.B(1). The NPAreq packet originated by node 1,1 is rebroadcasted by the producer side nodes, once per node. One NPArep packet is replied over each node. Therefore, the number of transmitted packets is 5 x 10 - 2 = 48 . As described above, this name prefix advertisement procedure is repeated every 10 second.

On the other hand, when the consumer (node 4) sends the first Interest packet, it will flooded throughout the consumer side node network. In this case, eleven nodes including the consumer itself are in the consumer side. Therefore, the first Interest packet is transmitted 11 times (rebroadcasted 10 times) in the consumer side. In the producer side network, it is forwarded once per a producer side node; 19 times in total. Therefore, in the case of the first Interest packet, it is transmitted 30 times. Since it establishes an FIB entry in the consumer side node, the following Interest packets are sent through the shortest path to the producer 1,1. When node 4 is in the area of node 3,1, it is 3 hops.

When node 4 moves to the area of the next consumer side node, e.g., from node 3,1 to node 3,2, it is detected in a way such as the link level retry-out. Then, the consumer repeats the same procedure as the first Interest packet.

As for the Data packets from node 1,1 to node 4, we suppose that the shortest path is applied.

Figure 3.14 shows the time variation of the number of transmitted packets for our proposal. NPAreq and NPArep packets are transmitted at every 10 second, the number is 48. At other timings, the number is zero. When sending the first Interest packet and when the consumer node changes the upstream node to the producer (every 10 second), the number of flooded or forwarded Interest packets becomes 30 or 31. At other timings, the number of transmitted Interest starts from 3 and goes up to 12 for each content request. The number of transmitted Data packet is 3 through 12 for each content request.

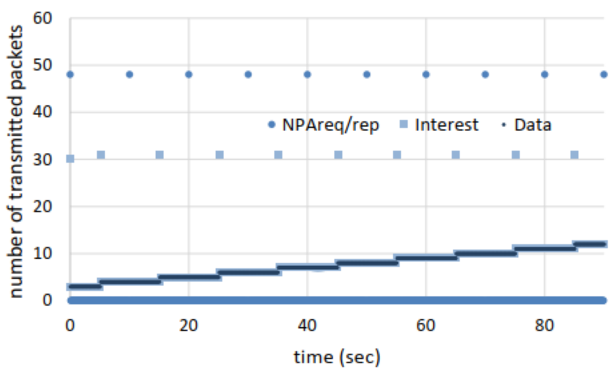


FIGURE 3.14: Time variation of total transmitted packets for Proposal

(2) TOP-CCN

In the case of TOP-CCN, the route setting is also performed at the beginning in the following way. As given in Figure 3.13 (b), there are 9 PMPR nodes and 18 MPR nodes when the consumer is located in the left-most position. In this case, the number of CA packets required for the route setting is calculated similarly with IV.B(2). That is

$$2 \times 4 + 18 \times (4 + 9) + 9 \times (5 + 9) = 368$$

After that, each node sends a CA packet once per one second for keeping the neighborhood relationship. Next, when the consumer changes the upstream node to the producer from node 3,1 to node 3,2, the CA packets are exchanged in the following way. First, the consumer and the former MPA (node 3,1) broadcast a CA packet to report the change of network configuration. Then, node 3,2 report the change to PMPR node 2,2 by a CA packet. Receiving this CA packet, node 2,2 generate a multi-hop CA packet which will flooded among PMPR nodes. In the end, MPR nodes also report new routing information to their own MPR selectors. So, the total number of transmitted CA packets is

$$2 + 1 + 8 + 18 = 29$$

When the consumer moves to the area of node 3,3, the situation is a little different. Since the route information of PMPR nodes 2,2 and 2,3 changes, two multi-hop CA packets are flooded. The result is

$$1 + 2 + 2 \times 8 + 2 \times 18 + 55$$

As for the Interest and Data packets, the shortest path (minimum hop transmission) is selected.

Figure 3.15 shows the time variation of the number of transmitted packets for TOP-CCN. In this case, the number of CA packets is either 368 (in the beginning), 29, 31, 55 or zero. The number of the Interest and Data packets is an optimal one.

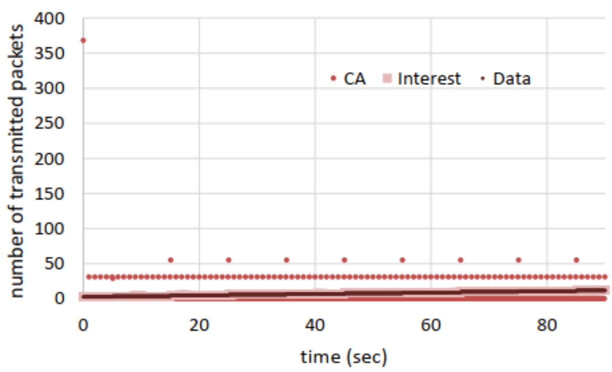


FIGURE 3.15: Time variation of total transmitted packets for TOP-CCN

(3) REMIF

In the case of REMIF, Interest packets are always flooded through all nodes except the producer. We suppose that Data packets are returned via the shortest path. Figure 3.16 shows the time variation of the number of transmitted packets for REMIF.

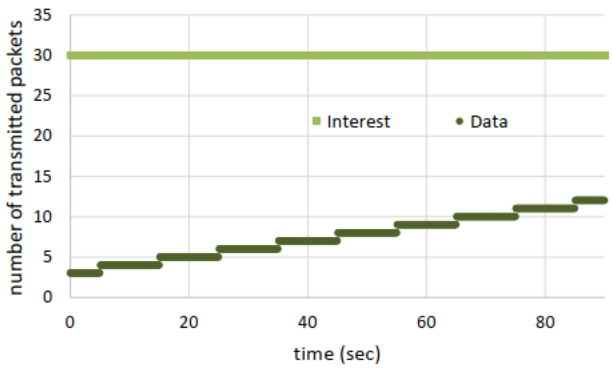


FIGURE 3.16: Time variation of total transmitted packets for REMIF.

(4) Summary

Figure 3.17 shows the time variation of the total number of all kinds of packets transmitted. In the case of TOP-CCN, large number of CA packets need to be exchanged at the beginning as described above. After that, CA packets need to be exchanged occasionally, and otherwise the number of packets is relatively low. In the case of REMIF, the number of packets is relatively high throughout the experiment. In the proposed method, the number becomes high occasionally, but it is lower than TOP-CCN, and otherwise, the number is similar with TOP-CCN. Table 3.2 shows the total number of packets throughout one experimental run. This table shows that the number of packets in the proposed method is smallest among the tree methods discussed here.

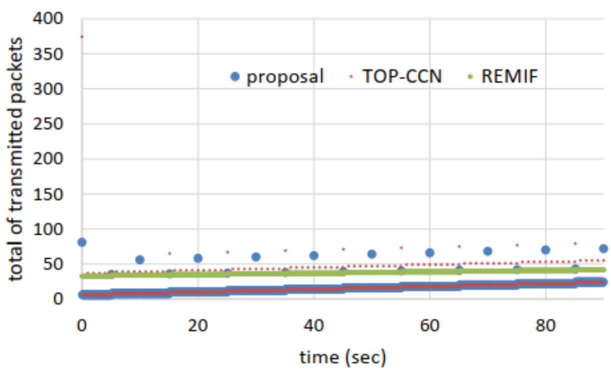


FIGURE 3.17: Time variation of total transmitted packets

TABLE 3.2: Total number of transmitted packets throughout experiment

Proposal	TOP-CCN	REMIF
14,220	17,133	33,783

3.3.3 Simulation Experimental

The previous theoretical analysis method assumed very simple radio transmission where only the distance decides the receipt or non-receipt of random it does not consider the node movement,and considers very simple moving model where only one consumer moves in a linear direction. They do not consider MAC layer re-transmission.

We simulate our design by using ns3-based simulator for NDN network called ndnSIM [40], a widely used NDN simulator implemented over the ns3 network simulator [41]. NS3 is a discrete random event driven network simulator and be widely used on many current researches. Ns3 has detailed network module and routing protocol, a real simulation for subsequent application in engineering and its result are closer to the real project [94]. Our experiment modelling uses physical layer WIFI implementation of ns3 that includes OFDM based IEEE 802.11 standard, constant speed propagation delay model and Nakagami propagation loss model. Furthermore, on MANET scenario we use Randomwalk2D mobility model simulate the random movement of node. The validation of WIFI modeling has been showed on many previous researches [97] [98] [99]. Based on this modeling, we aim to simulate a simple NDN-based MANET scenario where mobility nodes move around such as on the same floor of shopping mall or small park and request content related to that specific area from the content distributor and evaluate the effectiveness of our proposal on aspect of number of total transmitted packet that appropriate to our research goal and these modeling also are widely used by many major researches on Wireless Ad Hoc network field [95] [96].

The ndnSIM simulator follows the design of NDN architectures that originally built for wired network configurations and more modification in ndnSIM structures helps to incorporate with wireless network is required. For instance, a logical face indicates one point-to-point link to one connected neighbor. However on wireless communication, the device commonly has only one WiFi interface represents for one FACE that all neighbor is indicated via same FACE that each node have to be identified by the node identifier (e.g., MAC address). We also discuss a detailed way of implementing NDN-based protocol on wireless network over ndnSIM.

Discussions on Implementing NDN Wireless Ad Hoc Networks

As described above, how to implement NDN based wireless ad hoc networks is not discussed well. One of the major reasons will be that, in a wireless ad hoc network, a neighbor node needs to be identified by its MAC address and that the neighborhood relationship will be changed according to the node mobility. Another reason is that one interface that is used for receiving Interest/Data packets is also used for re-sending them to another neighbor, as suggested in [49].

We show two possible approaches for implementing NDN based wireless ad hoc networks over the ndnSIM simulator. As stated in the original proposal on NDN [42], it is possible that the content transfer function using Interest and Data packets (content chunk layer) works over TCP/IP protocol stack. Figure 3.18 shows a network architecture of NDN ad hoc network, where the UDP socket interface (the UdpFace class in ndnSIM) is used. Nodes (a consumer, a producer and an intermediate route) is connected via an ad hoc mode WLAN, and each node is assigned with an IP address. The neighbor node detection and the route establishment are realized by some ad hoc routing (OLSR in the figure). Interest and Data packets generated at the content chunk layer (the Forwarding-Strategy class in ndnSIM) are sent directly to their destinations through UDP/IP sessions. That is, the NDN intrinsic mechanisms, such as the suppression of Interest packet transfer by PIT and the use of Data packets in CS, are not performed in intermediate nodes. We use this implementation approach in the evaluation of OLSR based NDN ad hoc network in the next section.

Another approach is handling WLAN communication within the content chunk layer. The following are the outline of the implementation of wireless ad hoc network over ndnSIM.

• The content chunk layer (the ForwardingStrategy class) is located on top of IEEE 802.11 wireless LAN.

• A pair of face and MAC address is used to identify a neighbor node in the PIT and FIB handling.

+In the PIT handling, a MAC address is added in the classes of incoming face and outgoing face which are stored in a PIT entry. In the PIT entry look up for selecting downstream node to pass a Data packet, the MAC address of the Data packet sender is checked together with the incoming face ID.

+In the FIB setting, a MAC address is also kept in an FIB entry. When an Interest packet is received and its name is examined in the FIB, the MAC address of an upstream node is obtained together with the outgoing face ID.

• MAC addresses are handled in the WiFi network device (WifiNetDevice) class, and the ForwardingStrategy class cannot handle them. In order to allow the ForwardingStrategy class to handle MAC addresses, a remote MAC address is added in the Node class which maintains general information of a network node. When a WLAN frame is received, its source address is set in this field at the WifiNetDevice class and can be accessed in the ForwardingStrategy class. When a WLAN frame is sent, its destination MAC address is set at the ForwardingStrategy class and is reported to the WifiNetDevice class.

• In the Interest packet forwarding in the ForwardingStrategy class, the check whether the incoming face and the outgoing face obtained from FIB is the same is disabled.

We use the second implementation approach in the evaluation of the proposed method and REMIF in the next section.

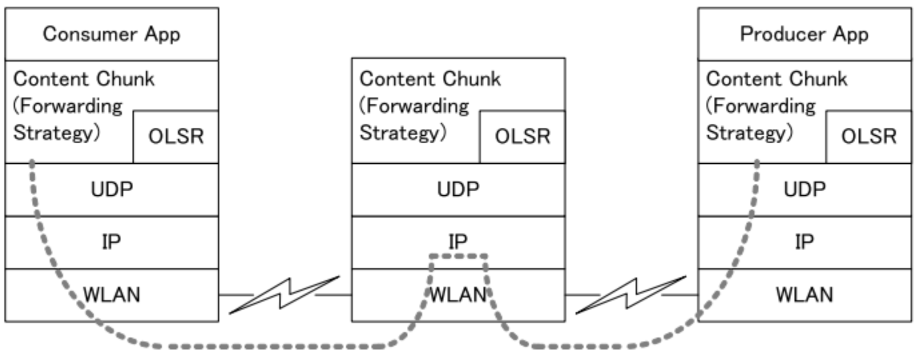


FIGURE 3.18: Communication sequence between consumer and producer.

Simulation Environment

In this section, we describe the results of performance evaluation using the ndnSIM simulator version 1.0.

Simulation Conditions

Figure 3.19 shows the network configuration used in the simulation. In the fields of 300 m by 200 m, four fixed nodes are located in a grid configuration with 100 m distance. The location of these nodes are fixed through a simulation. In addition, ten consumer side nodes are deployed randomly with the center of (200, 100). These nodes move around according to a random walk model. All nodes communicate with each other through ad hoc mode IEEE 802.11a protocol. Among the producer side nodes, the node located at the position (0, 0) works as a producer. As for the consumer side, two nodes work as consumers requesting different content. So, the data packet caching is not effective in the simulation.

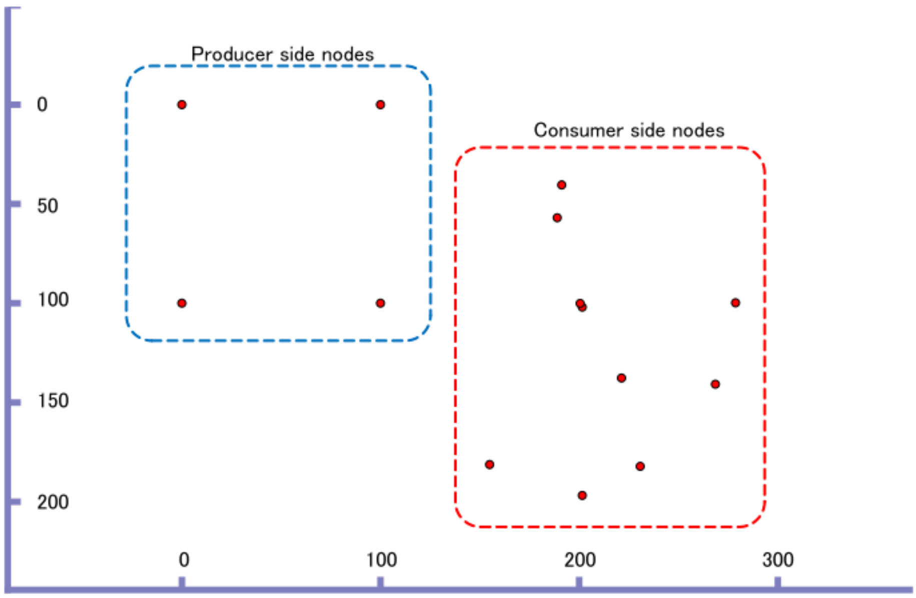


FIGURE 3.19: Network configuration for simulation.

The details of simulation condition are given in Table 3.3. As for the radio propagation, we used a setting used commonly in the ns3 simulator. The data rate in IEEE 802.11a is 24 Mbps constant. The consumer side nodes move around according to the 2 dimensional random walk model with the constant mobility speed, where nodes change their direction at every 2 second. We adopted the mobility speed of 40 m/s, 20 m/s, and 10 m/s. Those values are large as a moving speed of human, but they are adopted for changing the wireless connection during a 15 second simulation run. Among the producer side nodes, the node located at the position (0, 0) works as a producer.

TABLE 3.3: Simulation parameters.

Parameters	Detail
Radio Propagation	Constant speed propagation delay model, three log distance, Nakagami propagation loss model.
Wifi Data Mode	OFDM rate 24 Mbps
Mobility Model	Random Walk 2D model, course change at every 2 second. Mobility speed = 40 m/s , 20 m/s , or 10 m/s.
Consumer	Two nodes. Different content/same content. 10.0 through 10.3 Interests/s.
Producer	Node at (0,0). Data packet size = 1200 bytes.
Cache size	1000 packets at each node.
Evaluation	15 seconds for each simulation run. 10 seconds for Interest packet origination, 5 seconds for timeout re-transmission

Evaluated Methods and Their Implementation Details

The methods evaluated in this section are the proposed method, REMIF (simplified version), and NDN over UDP/IP ad hoc network with OLSR routing (OLSR based NDN). OLSR based NDN is used in order to estimate the performance of TOP-CCN, because the exchange of Hello and TC (Topology Control) messages corresponds to that of CA packets in TOP-CCN. On the other hand, OLSR based NDN uses the IP based routing in intermediate nodes as shown in previous Discussions on Implementing NDN Wireless Ad HocNetworks section, and even if all consumers request the same content, the Data packet caching is not effective. So, when the same content is used, OLSR based NDN can be used to estimate an IP based ad hoc network.

The following describe the details of the implementation of three evaluated methods.

(1) REMIF

FIB is not specified, and Interest packets are always transferred with the destination address set to broadcast MAC address ("ff:ff:ff:ff:ff:ff"). On the other hand, PIT is used for returning Data packets to consumers. When a new Interest packet is received, the incoming face and the source MAC address of the Interest packet is stored in a new PIT entry. Since it is possible that the identical Interest packet is received via a different path, the duplication is detected by the Interest nonce stored in this PIT entry. A re-transmitted Interest packet from a consumer contains the same nonce as the original Interest packet. In order to handle re-transmitted Interest packets properly, a PIT entry for which a Data packet is not returned needs to be discarded when its lifetime expires. The lifetime of a PIT entry is set to the lifetime of Interest packet, 500 msec in this evaluation.

Since REMIF uses the broadcast in transmitting Interest packets, we observed a mis-ordering problem given in Figure 3.20. Node 1 (a consumer) broadcasts an Interest packet in step (1) and node 2 rebroadcasts it in step (2). Then, node 4 (a producer) sends a Data packet to node 2, which transfers it to node 1 in step (3). After that, node 3 rebroadcast the Interest packet that is received in step (1). Since the PIT entry in nodes 1 and 4 are erased in step (3), they try to send the corresponding Data packet (node 1 has a cache for this Data packet). The Data packet is sent by node 1 to node 3, and node 3 returns it to node 1 again in step (5). Node 4 sends the Data packet again to node 3, which transfers it to node 1 in step (6). In both cases, the received Data packet is ignored because there are no corresponding PIT entry in node 1.

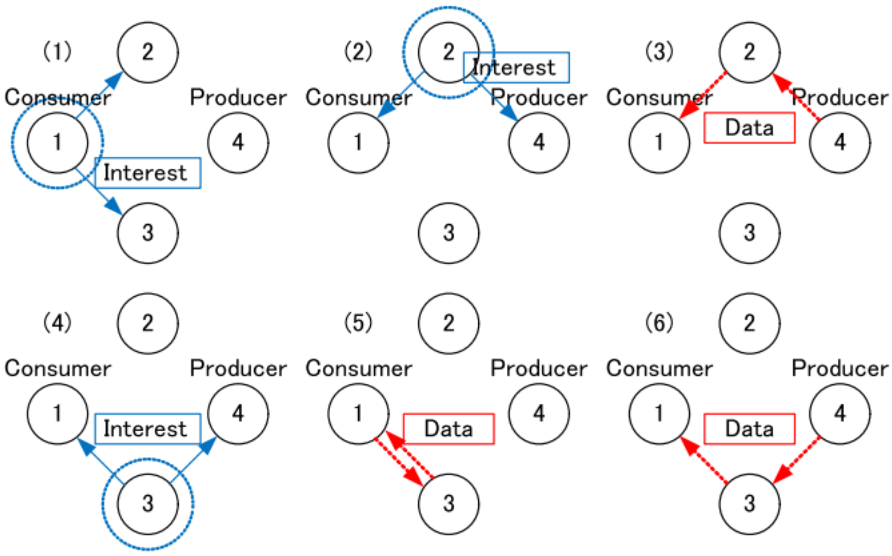


FIGURE 3.20: Mis-ordering in REMIF.

In order to avoid such a problem, we took the following way. In the PIT handling in the ForwardingStrategy class, when a Data packet is received, the records for incoming faces and outgoing faces are cleared, and then the PIT entry is erased by setting the PIT entry pruning timer. In the default, this value is set to 0 and the PIT entry is removed instantly. In this evaluation, we set this timer value to 50 msec. This means that our implementation ignores duplicate Interest packets received during 50 msec from the Data packet handling.

(2) Proposed method

In the performance evaluation here, we focus on the protocol behavior and the routing overhead when consumer side nodes move around. So, as for the routing protocols for producer side nodes, we set the FIB by hand before simulation runs start. We implemented the FIB handling behavior in consumer side nodes by extending the REMIF program described above. At first, when a consumer side node receives an Interest packet, it looks for an FIB entry matching the name prefix included in the Interest packet. If there are no entries, it creates a new entry for the name prefix with the default face and the broadcast MAC address. A consumer side node transmit the received Interest packet according to the corresponding FIB entry. When a consumer side node receives a Data packet, it registers the face from which the packet is received and the source MAC address of the data frame containing the Data packet in the corresponding FIB entry, if the MAC address in the entry is the broadcast MAC address.

When the network configuration of consumer side nodes changes, the FIB needs to be reconstructed. We implemented this mechanism in the following way.

• In order to detect the route change in consumer side nodes, we use the PIT entry pruning timer described above. When this timer is expired, the incoming and outgoing faces in the PIT entry examined. If they remain in the entry, we can decide that the Data packet corresponding to an Interest packet is not returned. These checks are executed in the PIT related class (the PitImpl class, specifically).

• If this timeout occurs consecutively (three times in our implementation), we decide that the route change occurs. Then, the outgoing face in the PIT entry is checked and, if the outgoing face has a unicast MAC address, the routine for clearing FIB entry in the ForwardingStrategy class is called.

• In the clearing FIB entry routine, the MAC address is set to the broadcast MAC address.

(3) OLSR based NDN

The OLSR based NDN method is implemented as the first approach described in previous Discussions on Implementing NDN Wireless Ad Hoc Networks section. We can use the OlsrHelper class supported in the ns-3 simulator and the IpFaceHelper supported in the ndnSIM simulator. It should be noted that the calling of "Bing()" in the "CreateOrGetUdpFace()" method in the IpFaceStack class needs to be commented out, in ndnSIM version 1.0.

Simulations Result

(1) Overview

We conducted three kinds of performance evaluation. The first is that using two consumers by changing the mobility speed. The second is that changing the number of consumers from two to eight with 20 m/s mobility speed. In these evaluations, individual consumers retrieve their own content, that is, no cache mechanisms are used. The third one is that where all consumers request the same content. In this case, cache mechanism is effective for REMIF and the proposed method. The conditions of the third evaluation is similar with that of the second evaluation.

In the evaluation for REMIF and the proposed method, we evaluated the following features, by changing the mobility speed of consumer side nodes or the number of consumers:

- Total number of Interest packets originated from consumers.
- Total number of Interest packets actually sent from consumers (including retransmissions).
- Total number of Data packets consumers received.
- Total number of forwarded Interest packets by all nodes.
- Total number of forwarded Data packets by all nodes.

In the evaluation for OLSR based NDN, we evaluated the following features:

- Total number of Interest packets originated from consumers.
- Total number of Interest packets actually sent from consumers (including retransmissions).
- Total number of Data packets consumers received.
- Total number of Hello and TC messages used in OLSR.

As for the sending interval of Hello and TC messages, we selected 0.5 sec and 1 sec, respectively. In order to establish routing information in the evaluation of OLSR based NDN, we introduce 5 second period before starting the content retrieval. In other word, simulation runs for OLSR based NDN take 20 seconds, consisting of 5 seconds for routing information setting, 10 seconds for Interest packet origination, and 5 seconds for timeout re-transmission.

(2) Results of evaluation by changing mobility speed

Figure 3.21 through Figure 3.23 show the results of the first performance evaluation. In the following figures, we normalize the number of packets by the total number of Interest packets originated from consumers. By adopting this normalization, the number of Data packet received by consumers shows the data delivery ratio.

In this evaluation, we selected three sets of two consumers and calculated the average of the three results. We used the same sets for REMIF and the proposed method, and other sets for OLSR based NDN, because OLSR based NDN uses 5 second route setting in the beginning of evaluation.

Figure 3.21 shows the total numbers of Interest and Data packets that consumers sent and received actually. The number of Interest packets is one through four times of that of the original Interest packets. The three methods have a similar tendency. Similarly, the number of Data packets that consumers received, i.e., the data delivery ratio, is 1 except the case of OLSR based NDN with 40 m/s speed, in which case the value is 0.99. With the 5 second re-transmission period, almost all Interest packets are satisfied by the corresponding Data packets.

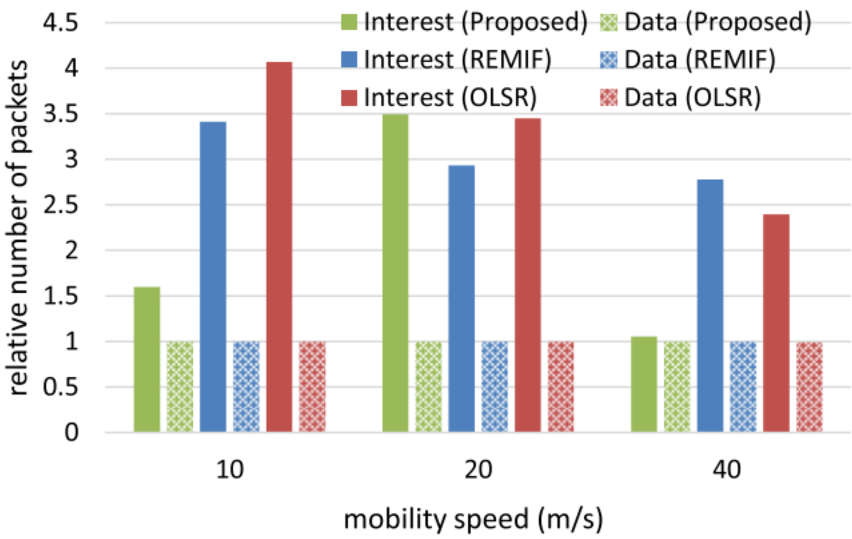


FIGURE 3.21: Numbers of Interest and Data of consumers (normalized by originated Interests; changing mobility speed).

Figure 3.22 shows the numbers of Interest and Data packets forwarded by all nodes in the network. Except the Interest packets in REMIF, the numbers are several times of the original Interest packets. The number of forwarded Interest packets in REMIF is more than twenty times of that of the original Interest packets.

Figure 3.23 shows the overhead of OLSR, i.e., the numbers of Hello and TC messages during the Interest origination and re-transmission period. From this result, it can be said that the overhead of OLSR routing messages is not very large.

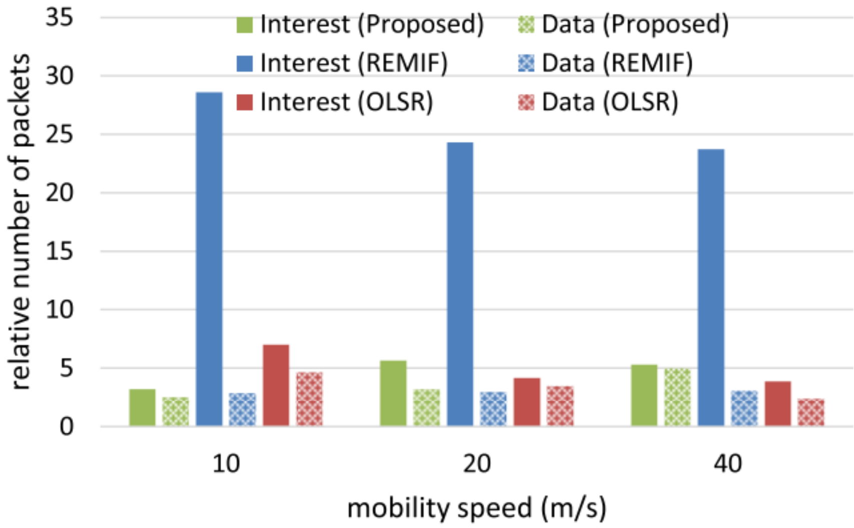


FIGURE 3.22: Numbers of Interest and Data of all nodes (normalized by originated Interests; changing mobility speed).

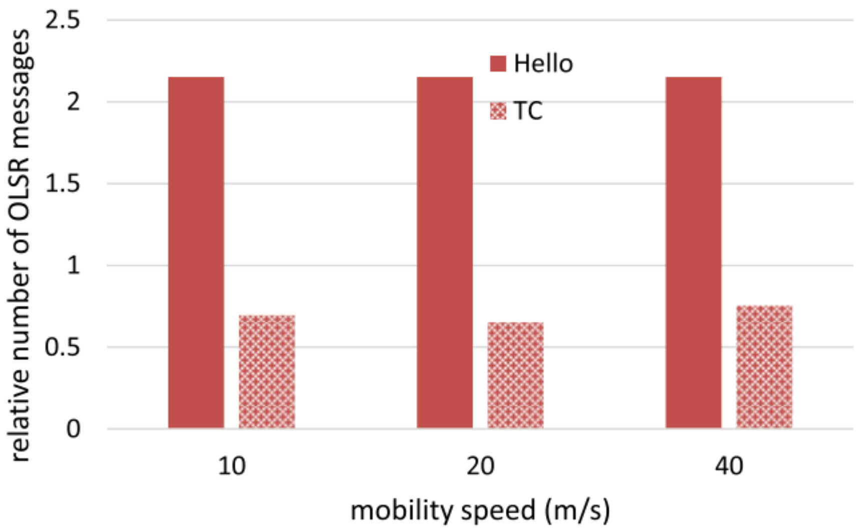


FIGURE 3.23: Numbers of OLSR Hello and TC messages (normalized by originated Interests; changing mobility speed).

Those results with two consumers show that although the number of forwarded Interest packets in REMIF is large, the data delivery rate is high for three methods, and that the mobility speed examined here does not affect the performance so much.

(3) Results of evaluation by changing number of consumers

On (3) and (4) experiments, we varies on consumer side, two, four, six, or eight nodes work as consumers requesting different content or the same content. If each consumer requests different content, the Data packet caching is not effective in the simulation. If the same content is used for all consumers, the caching will be used effectively.

Figure 3.24 and Figure 3.25 show the results of the second performance evaluation. Here, we changed the number of consumers, which request their own content, from two to eight. The mobility speed is set to 20 m/s. It should be noted that the vertical axis is logarithmic in those graphs. In this evaluation, we selected one set of consumers individually for two, four, six, and eight consumer cases.

Figure 3.24 shows the total numbers of Interest and Data packets that consumers sent and received actually. The proposed method and OLSR based NDN have a similar tendency, but the data delivery ratio is high for the proposed method. When there are eight consumers, the ratio of the proposed method is 0.85 and that of OLSR based NDN is 0.52. On the other hand, the performance of REMIF is worse than the others. In the case of eight consumers, the number of Interest packets actually sent by consumers goes to as high as 32.7 times that of original Interest packets, and the data delivery ratio goes down to 0.27.

Figure 3.25, giving the total numbers of Interest and Data packets forwarded through the network, shows a similar results. In the case of eight consumers, the total number of forwarded Interest packet is 242 times of the number of original Interest packets. The proposed method and OLSR based NDN also give similar tendency in this figure.

From the results with changing the number of consumers, it can be said that the performance of REMIF is worse than the others according to the increase of consumers requesting different content. It should be noted that the REMIF used in this section is a simplified version, which does not include the Interest suppression with deferring the Interest packet flooding randomly. But, we believe that the Interest flooding without FIB may be a problem when the number of consumers is large.

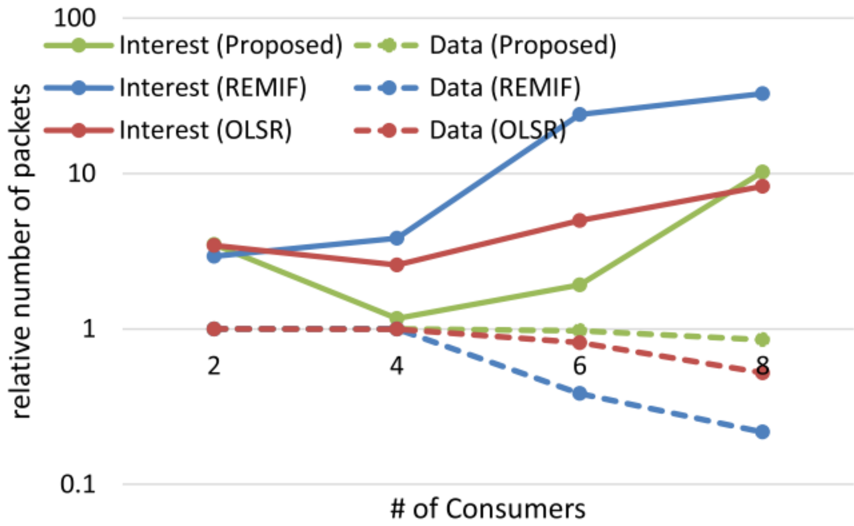


FIGURE 3.24: Numbers of Interest packets actually sent from consumers and Data packets received by consumers (normalized by originated Interests; changing number of consumers).

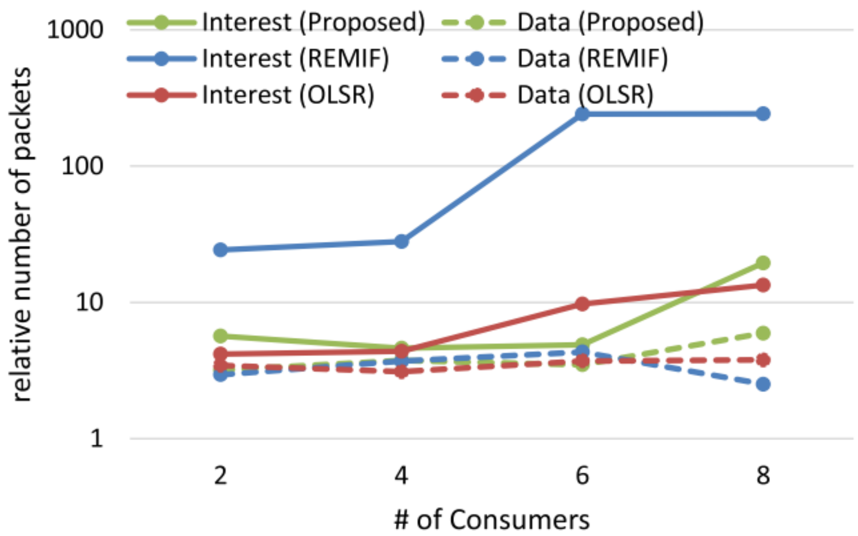


FIGURE 3.25: Numbers of Interest and Data packets forwarded by all nodes (normalized by originated Interests; changing number of consumers).

(4) Results of evaluation with Data packet caching

Figure 3.26 and Figure 3.27 show the results of the third performance evaluation. Here, all consumers request the identical content, and therefore the Data packet cache is expected to work effectively. The cache size of each node is 1,000 packets and the other conditions are the same as in the second evaluation. As described in previous Discussions on Implementing NDN Wireless Ad Hoc Networks section, the caching does not work in OLSR based NDN, and so, it indicates the performance of IP based ad hoc network in this evaluation.

In this evaluation, we selected one set of consumers for each of two, four, six, and eight consumer cases. It should be noted that there are at most 103 content data required in this experiment, and so 1,000 packet cache size is large enough to store all of requested data in each node.

Figure 3.26 shows the total numbers of Interest and Data packets that consumers sent and received actually. In this figure, the results of the proposed method and REMIF changed largely compared with Figure 3.24. The number of actually sent Interest packets is up to around twice of the original Interest packets. That of REMIF becomes less than 10 percents of Figure 3.24 in the case of eight consumers. The data delivery ratio of the proposed method and REMIF is 1 through this evaluation. On the other hand, the result of OLSR based NDN is similar with that shown in Fig. 12. In the case of eight consumers, the data delivery ratio is 0.59.

Figure 3.27 shows the total numbers of Interest and Data packets forwarded through the network. In this figure, the result of REMIF changed largely from that in Figure 3.25, although the number of forwarded Interest packets is still largest among the three method. In the case of eight consumers, the number was 242 times of that of original Interest packets, but it decreases to 12 times when the caching works well.

From those results, it can be said that the Data packet caching can reduce the traffic largely and that the performance can be increased compared with IP based ad hoc network.

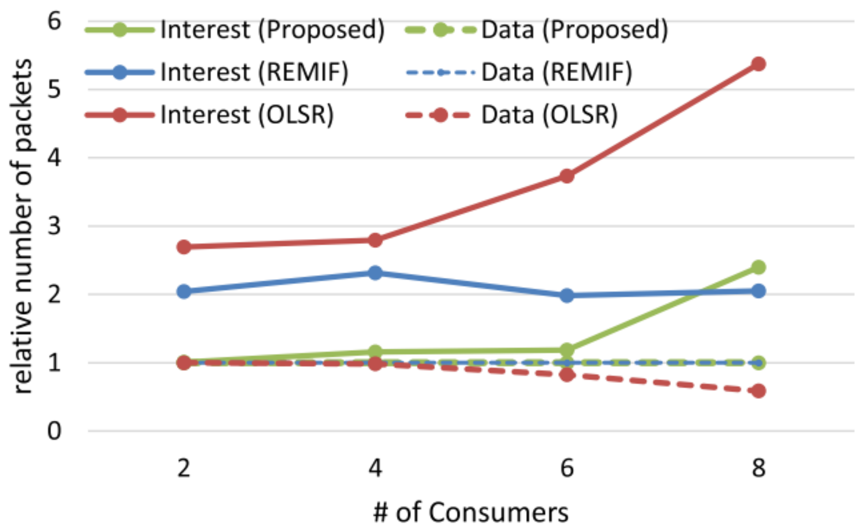


FIGURE 3.26: Numbers of Interest packets actually sent from consumers and Data packets received by consumers(normalized by originated Interests; consumers requesting same content).

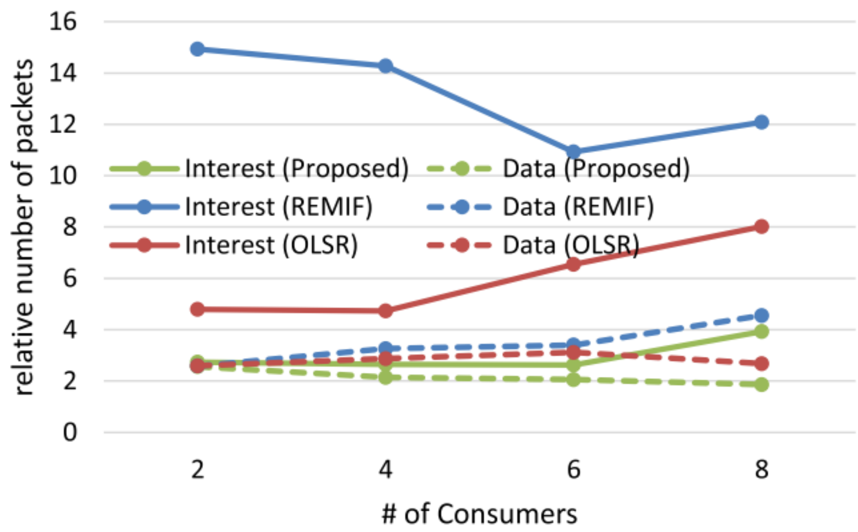


FIGURE 3.27: Numbers of Interest and Data packets forwarded by all nodes (normalized by originated Interests; consumers requesting same content).

3.4 Discussion

Comparison between simplified REMIF and original REMIF

We introduced a simplified version of REMIF in the evaluation. The features of the original REMIF are the random delay insertion in the Interest or Data packet forwarding, and the remaining energy check in the Interest forwarding. We did not implement either of them in our simplified REMIF. This means that nodes forward Interest and Data packets without any delay if necessary. As a result, a lot of unnecessary Interest and Data transmissions happened as described in previous implementation details of REMIF. So, we introduced some delay before releasing processed PIT entries (lifetime expansion of PIT entries), and succeeded in suppressing Interest forwarding for those arriving after the corresponding Data packet is processed. With this lifetime expansion and the identical Interest detection using nonce, the simplified REMIF floods only necessary Interest packets, i.e., at most one Interest per node.

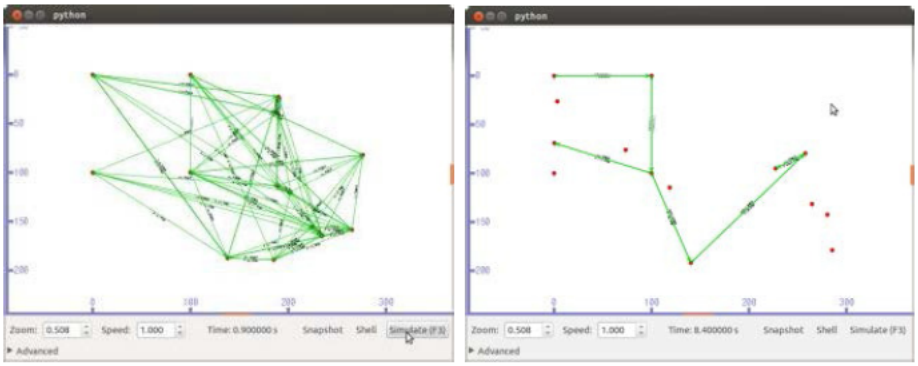
Figure 3.28 shows an example of communication log. This is the beginning part of the log generated by the ForwardingStrategy class. Each line includes time, node id (from 0 to 13), method in this class, and other parameters including packet type and content name. The red part in the beginning indicates the Interest generation by the consumer (node 4). The blue part indicates the Interest packet for warding in the intermediate nodes and the producer (the producer is node 10). The green part indicates the Data packet forwarding. The rest is the discarding of Interest packets due to the duplication. Especially, the underlined part indicates the Interest discarding at node 10, where the corresponding Data packet is returned. This discard is done by the PIT entry kept during the extended lifetime. As shown in this log, unnecessary Interest forwarding is suppressed even in the simplified REMIF we used in the experiment. Therefore, we consider that the overhead of the simplified REMIF will be comparable with that of the original REMIF.

```
0s            4 ndn.fw:OnInterest(): Interest /test/0/%00
0s            4 ndn.fw:PropagateInterest(): Interest /test/0/%00 propagated
0.000123055s  9 ndn.fw:OnInterest(): Interest /test/0/%00
0.000123055s  9 ndn.fw:PropagateInterest(): Interest /test/0/%00 propagated
0.000123201s  8 ndn.fw:OnInterest(): Interest /test/0/%00
0.000123201s  8 ndn.fw:PropagateInterest(): Interest /test/0/%00 propagated
0.000123208s  6 ndn.fw:OnInterest(): Interest /test/0/%00
0.000123208s  6 ndn.fw:PropagateInterest(): Interest /test/0/%00 propagated
0.000123363s 13 ndn.fw:OnInterest(): Interest /test/0/%00
0.000123363s 13 ndn.fw:PropagateInterest(): Interest /test/0/%00 propagated
0.000123484s  7 ndn.fw:OnInterest(): Interest /test/0/%00
0.000123484s  7 ndn.fw:PropagateInterest(): Interest /test/0/%00 propagated
0.000123522s  0 ndn.fw:OnInterest(): Interest /test/0/%00
0.000123522s  0 ndn.fw:PropagateInterest(): Interest /test/0/%00 propagated
0.000123651s 10 ndn.fw:OnInterest(): Interest /test/0/%00
0.000123651s 10 ndn.fw:OnData(): Data /test/0/%00 received from app
0.000237215s  8 ndn.fw:OnInterest(): Interest /test/0/%00 duplicated
0.000237416s  4 ndn.fw:OnInterest(): Interest /test/0/%00 duplicated
0.000333801s  6 ndn.fw:OnInterest(): Interest /test/0/%00 duplicated
0.000333937s  3 ndn.fw:OnInterest(): Interest /test/0/%00
0.000333937s  3 ndn.fw:PropagateInterest(): Interest /test/0/%00 propagated
0.000333942s  9 ndn.fw:OnInterest(): Interest /test/0/%00 duplicated
0.000333995s  4 ndn.fw:OnInterest(): Interest /test/0/%00 duplicated
0.000334054s  2 ndn.fw:OnInterest(): Interest /test/0/%00
0.000334054s  2 ndn.fw:PropagateInterest(): Interest /test/0/%00 propagated
0.000334058s  1 ndn.fw:OnInterest(): Interest /test/0/%00
0.000334058s  1 ndn.fw:PropagateInterest(): Interest /test/0/%00 propagated
0.000334085s  5 ndn.fw:OnInterest(): Interest /test/0/%00
0.000334085s  5 ndn.fw:PropagateInterest(): Interest /test/0/%00 propagated
0.000334104s  7 ndn.fw:OnInterest(): Interest /test/0/%00 duplicated
0.000334128s 13 ndn.fw:OnInterest(): Interest /test/0/%00 duplicated
0.00033454s  10 ndn.fw:OnInterest(): Interest /test/0/%00 duplicated
0.00041208s   8 ndn.fw:OnInterest(): Interest /test/0/%00 duplicated
0.000559252s  5 ndn.fw:OnInterest(): Interest /test/0/%00 duplicated
0.000559307s  7 ndn.fw:OnInterest(): Interest /test/0/%00 duplicated
0.000559435s  1 ndn.fw:OnInterest(): Interest /test/0/%00 duplicated
0.000559557s  2 ndn.fw:OnInterest(): Interest /test/0/%00 duplicated
      . . . .
0.00114794s 10 ndn.fw:OnInterest(): Interest /test/0/%00 duplicated
      . . . .
0.00605196s  4 ndn.fw:OnData(): Data /test/0/%00 received from 10
```

FIGURE 3.28: An example of communication log of Interest and Data packet forwarding

Influence of moving speed

In the evaluation with changing the mobility speed given in previous section, the results did not vary largely. This is because the WIFI parameter setting we used in the ndnSIM simulator, which is the default setting in the ns3 simulator, provided large WIFI coverage concerning the experiment field we supposed. Figure 3.29 shows examples of snapshots drawn by the ndnSIM simulator for REMIF and the proposed method. As shown in this figure, it was possible that many nodes in the experiment field communicate directly with each other. As stated in implementations details of proposal section, a route recovery is invoked when consumer side nodes detect consecutive PIT entry pruning timeouts. In the evaluation with two consumers by changing mobility speed, this route recovery mechanism was not invoked, although there were several route recovery invocations when the number of consumers is four, six and eight. This will be a reason for the results that the mobility speed did not give large impacts to the performance.



(a) REMIF (b) Proposal

FIGURE 3.29: Snapshot of communication for REMIF and proposed method

Energy consumption

On this research we do not focus on the energy consumption aspect but due to the benefit of caching and mitigating overhead of packet, NDN-based method shows a better energy efficiency compares to the current Internet architectures. Generally, energy consumption is focused to three main aspects: Transmission energy, storage energy and energy related to heating, ventilation and air conditioning (HVAC) operations [82]. The factor transmission energy is related to number of packets transmitted on network which concerns to proposal motivation.

Authors of BDSS protocol on [83] shows a solution to save energy consumption by optimizing the hop-count to destination that reduce the number of packets and on performance evaluation section, the results of both BDSS and compared protocol LFTC proved that the energy consumption is directly proportional to the number of packets. Similarity, Authors on [84] has a solution to improve the content delivery performance for network on two aspects of cost and latency named EFDA, the results also shows that EFDA has lower cost than a previous method (LOMCF) and also has better result on energy consumption. We can conclude that the packet overhead effects to the energy consumption.

Our proposal is focusing on reducing the content delivery cost for network and has been proved by best results of the number of transmitted packets, based on this metric we can estimate that our proposal has better energy consumption compares to previous two methods.

Scalability and background traffic performance evaluation

To evaluate the performance of three methods when increase the size of network and number of background traffic created by consumers by changing to mobility nodes from 10 to 30 and among 30 nodes, we varied number of consumer from 2, 4 ,6, 8 and increases to 10 nodes (Previous was 8 nodes). We also normalize the number of packets by the total number of Interest packets originated from consumers to present the packet ratio on the same figure.

Figure 3.30 shows the total numbers of Interest and Data packets that two consumers sent and received actually. All of three methods have the similar tendency with previous performance evaluation. REMIF still has the highest overhead and lower delivery ratio (below 70 percents)compares to two other methods (nearly 90 percents). Our proposal has slightly higher overhear than OLSR in case of velocity equals to 10, the rest of results still show that our proposal has better performance than proactive protocol in aspect of packet overhead (from 1.1 to 1.5 times compares to 1.8 and 19.9 times).

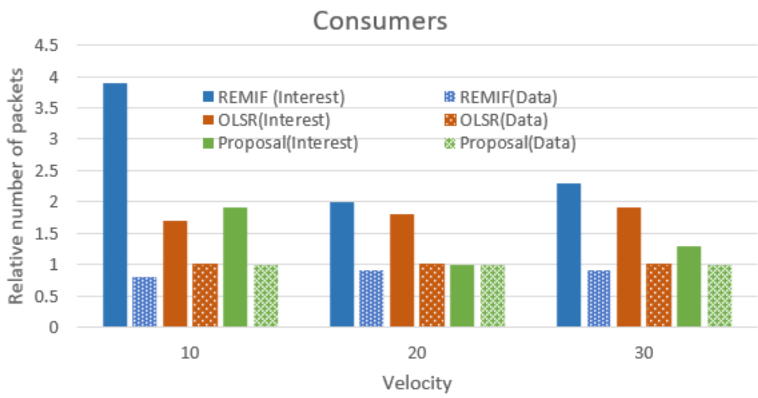


FIGURE 3.30: Numbers of Interest and Data packets of consumers (Mobility nodes= 30)

In Figure 3.31, the results shows that our proposal has the minimum packet cost overall especially in data packet cost (20 times compares to 50 times of REMIF and 40 times of OLSR).

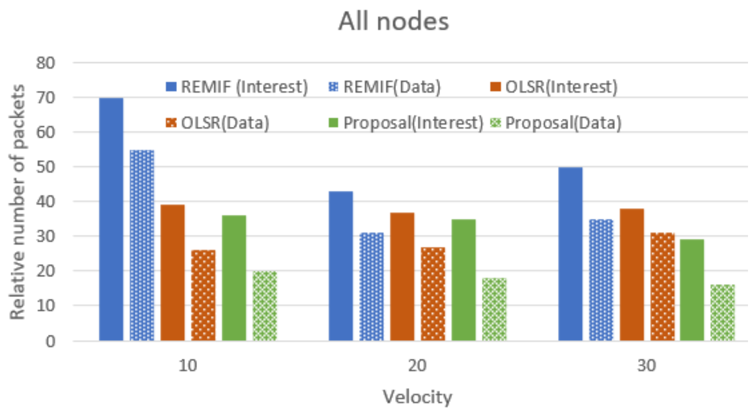


FIGURE 3.31: Numbers of Interest and Data packets of all nodes (Mobility nodes= 30)

Figure 3.32 shows the results of Interest and Data packet of all consumers when varies number of consumer from 2, 4 ,6, 8 and 10 among 30 mobility nodes. REMIF based on flooding method causes large network overhead (4 to 5 times of number of originated Interest). Due to trade off amount of control packet of OLSR, our proposal has slightly difference with OLSR (below 2 times compares to 2 times of OLSR). However due to the effective of caching on NDN, the number of Interest reduces when increasing the number of Consumers on both REMIF and our proposal. On the other hand, OLSR has a downward tendency without caching mechanism.

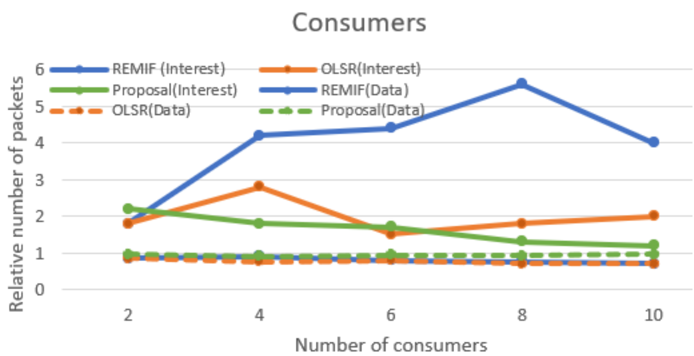


FIGURE 3.32: Numbers of Interest and Data packets of consumers (Mobility nodes= 30 same content, changing number of consumers)

The last Figure 3.33 shows the results of Interest and Data of all nodes. REMIF shows a down trend result with benefit of caching, the packer overhead is decreasing with the addition consumers.The data packets cost of all three methods is similar about 10 times of number of originated Interest).

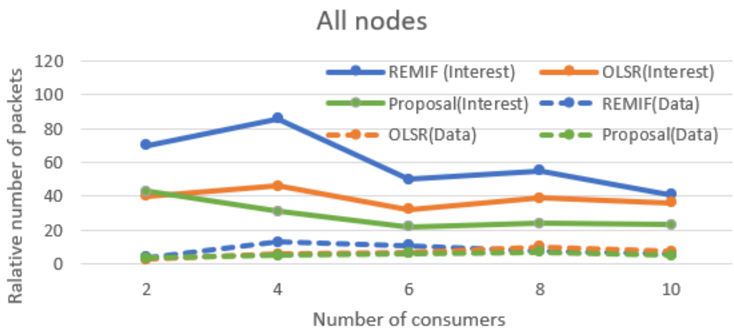


FIGURE 3.33: Numbers of Interest and Data packets of all nodes (Mobility nodes= 30 same content, changing number of consumers)

Credibility of simulation

The most problem of current simulators when simulating wireless network behaviors is inadequate modeling of the wireless physical layer especially the limitations of radio propagation models in simulators. If radio propagation model is appropriate, line of sight and the metric is evaluated in stable state (e.g. on wired network), the results is not changed largely. Authors on [103] compares the performance of simulators (ns2 and Qualnet) with real-world testbeds, the results shows that simulators still have a good match in experiments in simple environments like being outdoor with line-of-sight transmission even with multi bit-rate are used. Similarity, authors on [104] compares wireless network simulators (ns2, ns3) with testbed in corridor environment. Experiment set-up has WIFI modelling with Nakagami fading model and changing the position of the source and destination node along multi-hop chain for given number of hops, the results show that ns2, ns3 are similar with testbed results.

On these experiments, we do not add obstacle shadowing into our model but this factor influences on Ad hoc communication when the radio does not transfer along line of sight [106]. We believe that the radio propagation of our experiments have to be modeled and more investigated for each case to get accurate results as our future work.

3.5 Summary

In this chapter, we introduced a new hybrid routing protocol for NDN based ad hoc networks to address the RQ1, the concept of this design is dividing network into producer side includes fixed-nodes, and consumer side where mobility nodes move around. Producer side has stable connection adopts proactive approach to maintain the routing, and consumer side adopts reactive approach and not maintain any routing information due to the connection of node is unstable. The point of our proposal is that, in some ad hoc networks we are focusing on, the producer side and the consumer side can be clearly separated, and that the suitable routing mechanisms can be selected for each side. We provide a solution for RQ2 by replacing the logical FACE of default NDN to MAC Address to maintain the sender and receiver that operate multi/unicast communication.

We give a detailed description of the proposed mechanism with theoretical analysis in case of fixed nodes and simply moving nodes.

we also provide a detailed way of implement NDN architecture to wireless adhoc network over NDNsim simulator and simulated 3 performance evaluations where node moves around of the random walk type. The results of the performance evaluation show the followings.

• When the number of consumers is small, the proposed method, a simplified reactive routing (simplified REMIF), and a proactive routing (OLSR based NDN) have a similar data delivery ratio, although the number of flooded Interest packets is large in simplified REMIF. The mobility speed of consumer side nodes did not affect the delivery ratio so much.

• When the number of consumers requesting different content increases, the performance, i.e., the data delivery ratio and the routing overhead, of REMIF becomes worse. The data delivery ratio of the proposed method is better than that of OLSR based NDN supposing TOP-CCN.

• When the Data packet caching works effectively, the performance of the proposed method and REMIF is improved largely. The OLSR based NDN, which does not use the caching and therefore emulates IP based ad hoc network, has poor data delivery ratio than NDN based method. So, it can be said that the data caching is effective in the ad hoc network environment.

• When we increase the network size and background traffic by increasing the number of consumers, the results are not largely different with previous one, the results prove that our proposal also has capability with more large scale of network.

The results shows the effectiveness of the proposed method, but we think the performance evaluation with larger network is required. We also apply the NDN architecture to other type of AD HOC network is VANET in next chapter, where all nodes move faster and have chance to be producer.

Chapter 4

Visual Identification based forwarding strategy for V-NDN

4.1 Introduction

In this Chapter, we introduce a solution to answer RQ1 and RQ2 for high mobility of VANETs. Our proposal has the following two features.

First, to address the RQ1, we provides a full unicast-communication without using beacon message to reduce the network traffic overall. Our unicast-based forwarding is based on gathered information from neighbor in a beacon-less manner. Vehicle obtain the running around vehicle's visual information by using camera, create a visual information based identifier for each node called visual identifier (VI) which be used as next-hop ID on an unicast packet.

Second, for the RQ2, the concept of VI helps to recover function of FIB and PIT table by replacing incoming FACE and outgoing FACE by introducing new fields named Receiver-VI and Sender-VI which are identified separately, we also adds these new fields into Interest and Data to maintain the unicast communication once packet passes through node.

Our method is adopting two criterion: robust and lightweight. The goal of our deign is for supporting the driving assistance service where the driver gathers the road information ahead such as accident, traffic jam, slippery road etc, helps to keep a safe distance and have enough time for reaction before something happens and this information can be obtained more faster from the middle of the path from driver to area where event occurs by benefit of caching. By this way, the driver has a distance-vision of situation ahead and also helps the content is delivered only to appropriate Consumers to prevent the redundant information transmitted into network.

First, on such kind of scenario, Interest be used to request the information have to move forward as fast as possible that requires a robust forwarding method. "robust" in our term means despite of network topology changes, once look up the prefix on FIB table, appropriate entry is needed to exist constantly. The second criterion is lightweight, as we all know such kind of information has to updated periodically that causes network overhead, we want to design to minimize the traffic on network, thus possible to concede re-sources to other important safety information such as accident warning alert service.

The rest of this Chapter is structured as follows: Section 4.2 explains the detailed our new protocol. Section 4.3 shows the performance evaluation focusing on the network overhead, route cost in one-way and two-ways scenarios. Finally, Section 4.5 concludes this method.

4.2 Design Principles

We have adopted the following design principles for our visual-identification based forwarding mechanism shown in Figure 4.1.

• To support a full unicast communication, we obtain a new set of sender and receiver identifiers as add additional fields for Interest and Data packet which originally has only FACE field be used for every next-hop.

• We introduce a new Node Identifier called Visual Identifier (VI), VI is based on visual recognition by capturing the visual information of running around vehicles such as license number, color, type. VI helps node of NDN to divide the incoming Face and outgoing Face separately to deal with the FACE logic issue of NDN. We also maintain a neighbor table on each node individually (VI Table) on a beacon-less manner for next-hop selection process.

• We keep using FIB, PIT to take advantages of original NDN architecture about scalability problem, cache, content-centric data transmission and mobility. Aim to improve the capability of FIB and PIT, we replace the Face and Requester field by VI of node that help the next-hop forwarding associates with VI Table is easy to build and maintain. Through this way, we also eliminate the flooding-based discovery phase of NDN when table is blank by filling up the blank FIB and PIT entries with the candidate node elected from VI Table.

• In path recovery aspect, we design a free-packet method called check before transmit, node uses always-on camera to check the available of next-hop before sending packet, to prevent the broken link that trigger the broadcast mode, we recover that back to unicast mode by replace the non-alive by the new one selected from VI table.

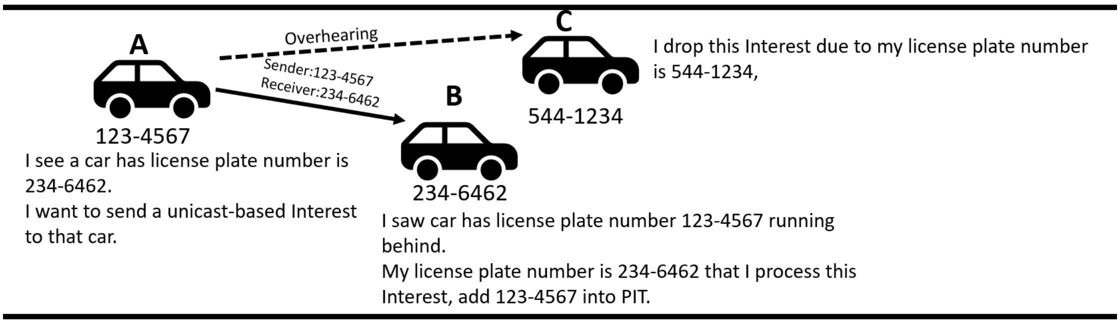


FIGURE 4.1: Visual information based unicast forwarding on NDN.

4.2.1 Visual-Identification Concept and Next-Hop Selection

The concept of visual-identification had implemented in various researches such as to identify and tag the malicious vehicles [44] or be used as a factor of authentication to improve the security issues [45]. Based on these benefits of using visual information, we have an idea to adopt it as metric on Interest forwarding protocol. We assume that all vehicles are equipped with front and rear cameras (drive recorders) which be used to capture the visual identifier of running around vehicles. Visual Identifier (VI) is the core of our design, the concept of VI is using high resolution camera to gather a combination of factors such as licenses plate number, color, brand, car type and others to identify and assign VI to each vehicle, VI is unique and is used as Vehicle Identifier as shown in Figure 4.2.

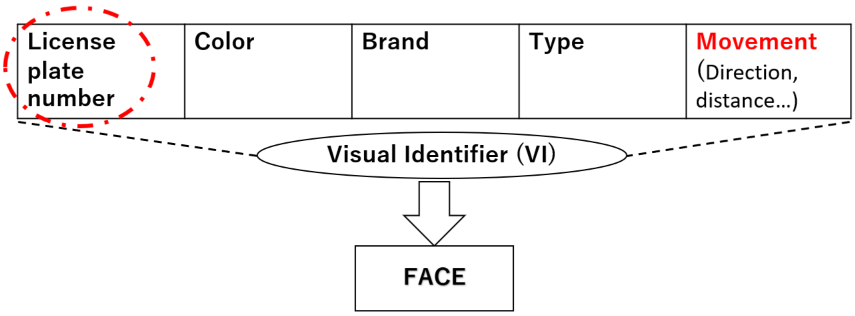


FIGURE 4.2: Generating VI based on Visual information.

On many previous researches, Node ID, MAC address, GPS position are used as Vehicle Identifier. There are two main issues when using these kind of node identifier.

• The common disadvantage of all of them are in a passive-based method. It means the neighbor ID information have to "receive" from the outside passively and node has a cost of control packet. For instance, Node ID and Position are included in arrived hello packet which periodically send by all nodes, or in other solution like my proposal for MANETs scenario when MAC address is added into Interest and Data packet. Thus the number of control packet grows highly with the increasing of number of nodes.

• The second problem is about beacon-message, the reliability of communication is relay on the accuracy of the beacon message. A fresh and update of neighbors information have to trade off a mount of control packet by increasing the rate of beacon, otherwise out-of-date beacon issue will occurs. For instance, due to the high velocity mobile nodes and predictable moving direction. Hence, during of two beacon message, the information of velocity or moving direction can be out of date that when select a next-hop, it leads to the wrong packet forwarding decisions such as passing the packet to the vehicle which running from opposite side or out-of-transmission that causes packet loss.

To encounter the above issues, our proposal focuses on VI as Vehicle Identifier to design a robust neighbor-maintaining method in the active approach. Vehicle equips both front and rear cameras helps to confirm the visual information on both way that able to confirms where the packet sent from and able to send packet to any correct direction at will. In aspect of network traffic, free-packet method by only uses camera to assign an identifier for each node based on visual information (license plate number), takes advantage of packet cost than using control packet (increase with the number of nodes) and Interest/Data (increase by number of flooding message when network topology frequently changed and has to recover) as already shown on result of three performance evaluations. Furthermore, as explained above, using VI encounter all the problems of movement on VANET in case of opposite forwarding, unreachable forwarding and also provide a real-time checking/updating helps reduces the loss and delay of transmission.

Table 4.1 shows the parameters contained in VI table. Although the license number is unique that can become the VI (VI of Car A = 433-234), in some cases license plate number not able to captured (bad weather, obstacle or lack of light, etc.), for that reason we have additional fields such as color, brand, or any other identifies to improve the recognition ability.

The ability of this image processing is varied on specification of cameras on physical layer or the photo analyzing algorithm on application layer, hence we assume that the transmission range of wireless ad hoc network is equal to the range of cameras in our design to make sure line of sight node is always reachable.

TABLE 4.1: Visual Identifier (VI) Table

Visual Identifier	**License Plate Number**	**Color**	**Brand**	**Distance**	**Car Type**	**Others**
CarA	433-123	Black	Nissan	50	Sedan	Driver wears hat
CarB	324-157	Red	BMW	70	SUV	

In fact that VANETs has a much higher mobility of vehicular moving, differ to MANETs in VANETs it is more difficult to maintain a stable end-to-end path between consumers and producers in proactive manner (Like OLSR protocol). Instead, we believe that in VANETs the end-to-end routing have to shift to neighbor-ware hop-by-hop routing that a reliable forwarding strategy is depend on the quality of the next relay node.

When node wants to route an Interest or Data, it looks up its FIB or PIT table to find out the Next-Hop/Requester make the decision called Next-Hop Selection Process. In traditional way of previous methods, this process is operated based on the neighbor information gathered from beacon message. The node has the metrics (such as distance, link state, direction, number of neighbor...) will be selected as the candidate node. Similarity, in our design we select the best next-hop based on VI Table, and to optimize the hop count we decide the distance metric (farthest in-range node) is the main factor to elect the candidate node. For Instance, in Table 4.1, among two vehicles identified as CarA and CarB, CarB is prioritized due to higher distance (70 compared to 50).

4.2.2 Packet Structures

We add three new fields into the Interest and Data packet. The detail of enhanced Interest and Data packet was summarized in Table 4.2.

• Sender-VI: This field represents the VI of sender (The previous hop-by-hop forwarding sender).

• Receiver-VI: This field represents the VI of next-hop which was selected from VI table.

• Lifetime: Reduced by one before Interest is forwarded to next-hop, Interest is discarded when the lifetime count is equal to zero.

TABLE 4.2: Parameters in Interest and Data Packet

Interest	Data
Sender-VI	Name
Lifetime	Sender-VI
Nonce	Signature
Name	Data
Receiver-VI	Receiver-VI

In our design, all the forwarding decision is based on FIB and PIT. An entry is created for an individual name prefix. The addition of VI concept to enhance the original FIB and PIT by switching Face into VI and also able to deal with direction of vehicle in the forwarding rather previous works. Table 4.3 and 4.4 show the forwarding parameter is the Node ID (VI) of upstream node in FIB and downstream node in PIT.

TABLE 4.3: Enchained Forwarding Information Base (FIB) Table.

Name	Next Hop
check	CarA

TABLE 4.4: Enchained Pending Interest Table (PIT).

Name	Requester
check	CarB

4.2.3 Forwarding Process

As described in Chapter 2, once NDN node forwards an Interest message, it looks-up a FIB entry for the prefix in FIB table and sends the Interest to the outgoing Face (the candidate node).

First Phase

When a vehicle wants to monitor the road condition ahead for driving assistant service, it is considered as a Consumer and initialize an Interest message. According to the design of NDN, at this point FIB table is empty, the initial Interest has to be broadcasted into network to discover the content, or the Interest can be forwarded in unicast only if and only if a candidate node is selected from neighbor list by using beacon message [46] (next-hop selection process). For this reason, both of them costs in term of traffic overhead, we encounter this limitation by taking advantage of previously explained VI idea.

As shown in (1) of Figure 4.3 as dotted-line, consumer selects the candidate node which has best metric among its neighbors, and creates a new FIB entry with VI of selected next-hop at once to fill up the empty FIB table. on (2) of Figure 4.3 The VI fields of initial Interest at this time contains Receiver-VI (The VI of candidate node) and also Sender-VI (The VI of the Consumer).

Once a intermediate node receives this Interest, it normally creates a PIT entry which correspond to the previous Sender (extract the Sender-VI field on Interest). After that node performs the following actions:

• It selects a candidate node from its VI table which has a best distance metric and creates a new FIB entry contains Next-Hop field equals to the VI of next-hop like the original Consumer.

• It replaces the current Sender-VI of the Interest message by its own VI, inserts the VI of next-hop into Receiver-VI field and forwards the Interest.

The Lifetime of the Interest is reduced by one every time the Interest passes a node. This process repeats until the lifetime equal to 0 or reaches the Producer. In our scenario, due to the road-event discovering purpose, the Producer is the node that produces a road-event. In case Producer receives the Interest, Producer returns the Data to satisfy received Interest and performs the following actions:

• Producer takes the Sender-VI (The VI of the previous hop) of the Interest message and puts it into the Data message as the Receiver-VI.

• It takes its own VI and inserts into the Sender-VI field of Data message.

• Producer returns Data to the Consumer through the reverse path of the Interest which is previously maintained by PIT on all intermediate nodes.

on (3) of Figure 4.3 when an intermediate node receives a Data message, its checks the Receiver-VI field of Data to make the decision. If this field does not match with its VI, the Data packet is discarded. In case Receiver-VI of Data is the same with node's VI, the node checks the PIT. Data is also discarded when no matching PIT entry. If a corresponding PIT entry exists, the node takes the following actions:

• It creates (or updates) a new FIB entry that contains the Sender-VI (VI of the previous sender)

• It inserts its own VI into the Sender-VI of Data message.

• Node sets the new Receiver-VI of Data message based on the next-hop field of matching PIT entry.

• Node sends this Data packet into network in unicast-based and also caches the Data in its CS.

This process continues until the Consumer receives the first Data message. The Consumer creates or updates the FIB entry contains the Sender-VI field of the Data message.

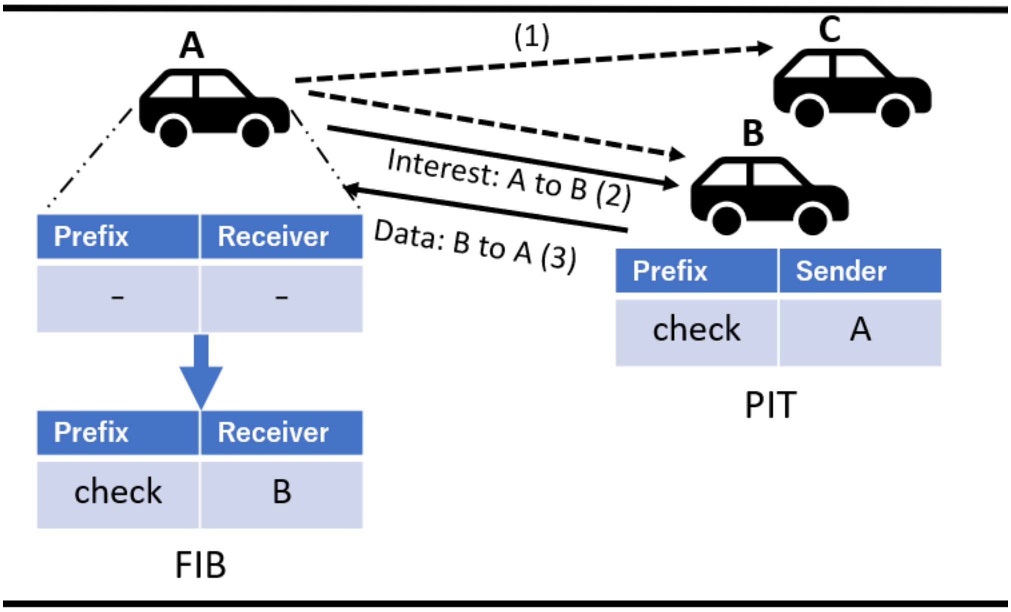


FIGURE 4.3: First Phase.

Second Phase

The Consumer checks its FIB Table to make the decision for the second Interest as shown in (3) of Figure 4.4 . In case matching FIB entry was found, node sends the Interest (set the Receiver-VI of Interest message to next-hop field of corresponding FIB entry). Otherwise node acts like the first phase to transmit the Interest message by looking-up the VI table (next-hop selection). In case Receiver-VI is matched, node move to NDN stack checking processing. If no match cache in CS, node will update the Sender-VI of Interest message into PIT entry and look up FIB table for the candidate node. Node inserts its own VI into Sender-VI, Receiver-VI is the VI of chosen next-hop, and send the Interest message.

On (4) of Figure 4.3, this Interest is forwarded until Lifetime becomes zero or arrives the Producers, the Data follows the PIT breadcrumb as mentioned in the first phase.

According to the goal of reducing redundant packet transmission in a lightweight way, in the second phase we minimize the path from Consumer to Producer by forwarding the following Interest of same prefix by FIB Table instead of using Next-hop selection by VI. Selecting next-hop on VI table in this phase will easily increase the number of routes points to the Producer thus traffic will grow and difficult to manage and maintain. Alternatively, we use VI concept to support path recovery function be explained in the following section.

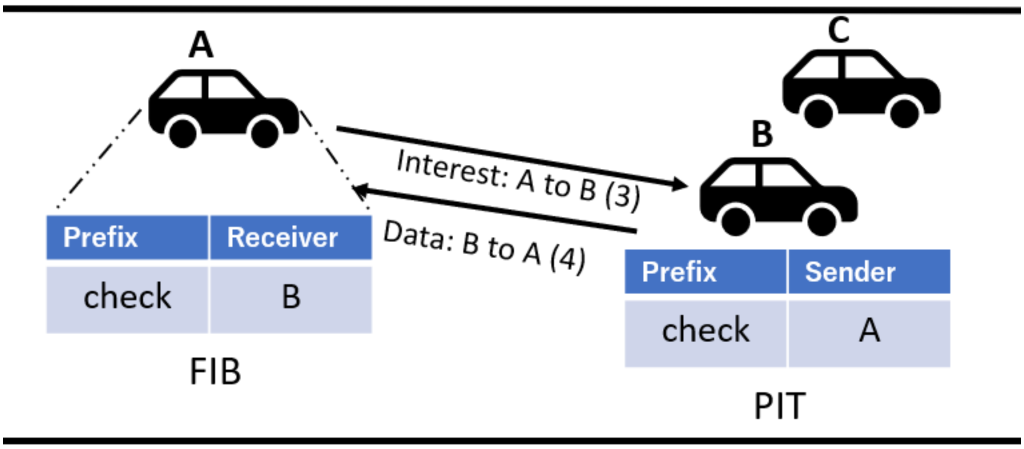


FIGURE 4.4: Second Phase.

Recovery Phase

As described in previous section, the characteristic of visual-identification process is in real-time, VI is captured by vehicle and added into VI table frequently. We have an idea to maintain and recover the route called "check before transmit mechanism", it can be displayed through the flowchart shown in Figure 4.5.

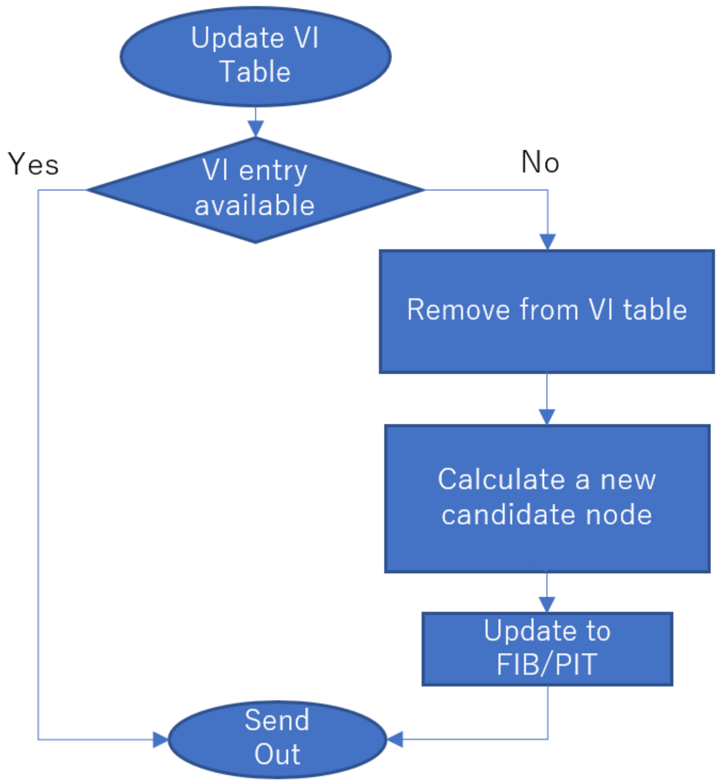


FIGURE 4.5: Check before transmit mechanism

To reduce the packet loss due to dynamic change of mobility and detect the broken-path in real-time and also in active-based, in our design node have to examine the neighbor and VI table periodically by camera, the VI of vehicle exits in VI table represents to the reachable node in real-time. Due to not using any protocol to populate the prefix, the next-hop field of FIB or Requester of PIT is updated based on VI Table entries (Next-hop selection process). The vehicle comes in-sight of camera is considered as the good candidate node as shown in (5) and (6) of Figure 4.6. For instance, one previous vehicle is become unable to visual recognize (not able to capture the number-plate or not enough factor to detect the VI), it is considered as an unreachable node, node will take the following actions:

• Node removes the out of range neighbor entries and update the new one to its VI table.

• It reactive the Next-hop selection process by re-calculating all the metrics to select a new candidate node among current neighbor nodes.

• Node replaces the unreachable next-hop on FIB table or PIT Table by the new next-hop and send out the massage.

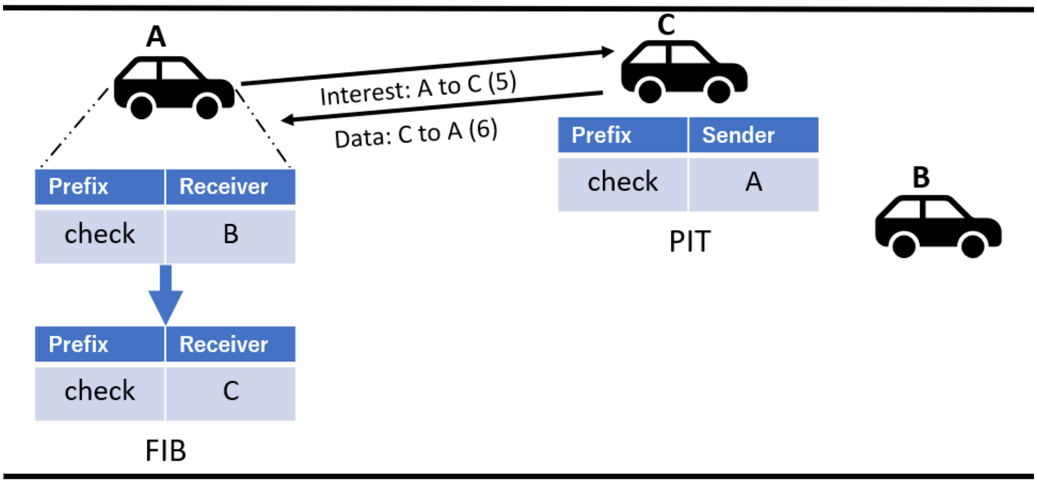


FIGURE 4.6: Recovery Phase.

Comparing with previous researches our check before transmit mechanism reduces the amount of retransmission messages and message for route recovery phase.

Improving the line of sight

In this section, we describe a way to improve the line of sight of camera in our design by determining two terms of invisible neighbor and visible neighbor. The capacity of visual-identification method relies on the vision of camera. However due to obstacle or angle of camera, in some case the running around vehicle is in-range of transmission but out of sight, or in line of sight but not be able to captured fully by camera that makes VI cannot be assigned. To encounter this problem, we introduce a mechanism to utilize both of kind of neighbor to exceed the line of sight of camera and also to reduce the lost of packet when applying this mechanism.

As shown in node Figure 4.7, B and C in transmission-range physically of A but C is out of vision due to angle of camera hence A maintains only B on its VI Table. All the neighbors if each node are shown in Table 4.5.

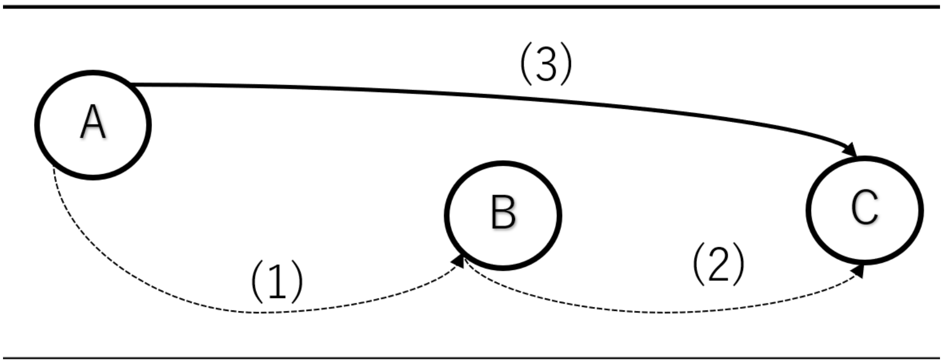


FIGURE 4.7: Improving the line of sight of camera

TABLE 4.5: The running around neighbor list.

Car	Visible Neighbor	Invisible Neighbor
A	B	C
B	A, C	
C	B	A

On (1) of Figure 4.7, when A want to send an Interest, A searches its FIB table, when no matching entry, A have to use Next-Hop selection process by using VI Table and B will be selected as next-hop. A sets Sender-VI to A, Receiver-VI to B and send out Interest into shared medium. This Interest arrives all neighbors of A are B and C, these two nodes take the following actions:

B Check out the Receiver-VI is B, it look-up VI Table to create new FIB entry for this Interest, B selects C as the candidate node, B sets Sender-VI to B and Receiver-VI to C and send out the Interest as shown in (2) of Figure 4.7.

On (3) of Figure 4.7, C also receives the Interest from A, before ignore this Interest(Receiver-VI is B), C has one step to check its VI Table and knows that B is the running behind vehicle (by rear camera), C considers itself is an Invisible Neighbor of A, put A into Requester field on PIT and set its own VI into Sender-VI to continue forwarding process.

When Interest from B arrives C, C checks nonce and knows that this Interest is the same as previous received Interest from A then C drop this Interest to prevent redundant traffic.

An example of network discovery in our method

From the second phase onward, the forwarding protocol works based on FIB and PIT in a traditional way of NDN model. Thus, we explain the detail about a communication session between a set of Consumer/ Producer in first phase or network discovery phase by the following example. Figure 4.8 shows that vehicle A, it looks up entries in FIB table before sending the Interest. In-range of camera, vehicle A captures the number plates and other specifications of running ahead vehicle B and C, and puts B and C into its VI table.

Figure 4.8 shows that vehicle A, it looks up entries in FIB table before sending the Interest. In-range of camera, vehicle A captures the number plates and other specifications of running ahead vehicle B and C, and puts B and C into its VI table.

VI	License Number	Color	Brand	Car Type	Distance	Other
C	345-326	Blue	Toyota	Sedan	50	

FIGURE 4.8: Vehicle A maintains the VI Table

Figure 4.9, at this time the FIB table of A is empty, A checks the VI Table to select vehicle C which has the best metric as the next-hop (the longest distance). A creates a new FIB entry for prefix “check” with forwarding candidate is vehicle C, puts its VI into Sender-VI and also VI of C into Receiver-VI field, send this Interest to C by unicast to retrieve the content as shown in Figure 4.10.

Prefix	Next-hop
-	-

Prefix	Next-hop
check	C

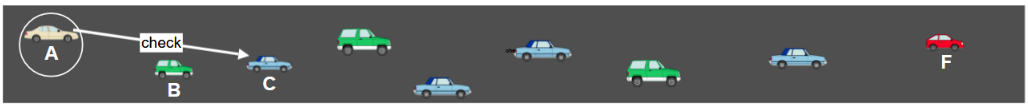


FIGURE 4.9: Vehicle A checks the FIB and create a new entry that points to vehicle C.

Name	Sender-VI	Receiver-VI
check	A	C

FIGURE 4.10: Vehicle A edits the Sender-VI and the Receiver-VI to send Interest.

Figure 4.11 shows the forwarding when vehicle C receives the Interest, C inspects the CS. Thus, no corresponding data, C creates a new PIT entry respond to A. Similar to the previous implemented process on A, C also selects a next-hop for “check”, adds a new FIB entry and send the Interest to D.

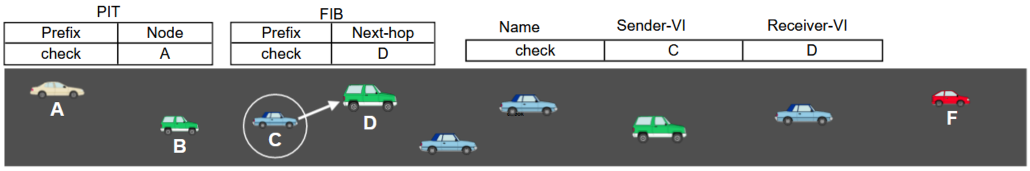


FIGURE 4.11: Vehicle C repeats the previous process to forward the Interest to vehicle D.

The intermediate node repeats this process sequentially to forward the Interest and update PIT simultaneously. Once the Interest reaches to area of vehicle F which has a warning of traffic jam ahead, vehicle F become Producer and terminate the Interest forwarding (Figure 4.12).

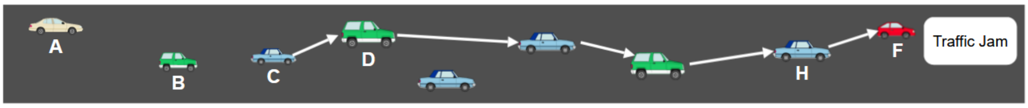


FIGURE 4.12: Intermediate node relays the Interest one by one until reaches to vehicle F which has a traffic jam information.

Figure 4.13 shows the return way of Data from vehicle F back to vehicle A through the path which is established by each intermediate nodes. F configures an appropriate set of Sender-VI and Receiver-VI and send back the Data to vehicle H. H continues to forward this Data to G and this process repeats until arrives to A.

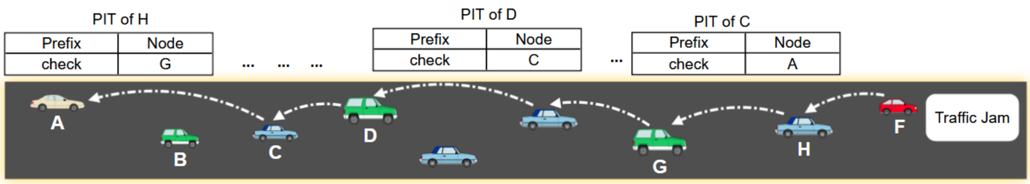


FIGURE 4.13: Vehicle F return the Data back to vehicle A.

4.3 Performance Evaluation

In this section we the describe the results of performance evaluation by using ndnSIM and SUMO to generate three vehicle traces (one-way and low density two-way scenario and high density two-way). Similar to previous chapter by using the same WIFI model to simulate to communication of vehicle to vehicle, we also use SUMO to define traffic flow and road network close to real world that appropriate to aim of our scenario to simulate vehicle runs on a straight road and maintains the road condition ahead. On this performance evaluation, due to our aim of research is mitigating the packet overhead of network, we focus on number of transmitted packet metric of packet level on simulation, these setting is widely used to calculated this metrics by many previous major researches [100] [101] [102].

4.3.1 One-way scenario

In One-way scenario, we want to evaluate the performance of our proposal compares to previous works in traffic costs and Interest satisfaction ratio.

Simulation Setting for One-way scenario

We set up a long road topology has two lanes and one-way traffic. Number of vehicles varying from 30 to 50 in 2500 m area. Vehicles run along the road with mini-mum gap between car is 30 m and velocity is randomly distributed from 30 to 40 km/h. All the nodes communicate through ad hoc mode 802.11a with 100 m trans-mission range are shown in following table.

TABLE 4.6: Simulation parameters.

Parameters	**Detail**
Number of Vehicles	30, 40, 50
Mac Protocol	802.11a 5GHZ
Transmission Range	100 m
Velocity	30 - 40 km/h
Transmission Rate	1 packet/second
Beacon Rate	1 packet/second
Simulation Time	200 seconds

Our scenario is traffic prediction supporting service when a Consumer at the beginning of the road area periodic sends Interest along the road to update the traffic information ahead at 1 packet/second rate. A traffic jam event is occurred at the end of the road, the node in this area becomes Producer and responds all the satisfied Interest. In addition, during the simulation time we remove one intermediate node for one time to simulate the disconnected network and evaluate the path recovery function on each method.

Due to the goal of our proposal is reducing the redundant traffic, our evaluation focuses on the packet costs and the efficiency of each method, we use 4 metrics to evaluate the routing protocols by changing the number of nodes:

• Overhead of control packet: The total number of control packets are sent by all relative nodes.

• Interest packet transfer: The total number of Interest sent by Consumer and intermediate nodes includes re-transmission.

• Total transmitted packet: Total number of control packet, Interest and Data are sent by all relative nodes.

• Interest Satisfaction Ratio (ISR): Obtained from the total number of Data returned divided by the total Interest sent of Consumer to evaluate the accuracy of each method.

We evaluate the performance of our proposal compares to GPSR based NDN and MMM-VNDN protocol. The first one is GPSR, a typical IP-based VANETs which uses beacon message to maintain the neighbor list, we use the UdpFace class in ndnSIM to simulate GPSR [47] method under NDN layer, it was detailed explained in our previous research [48]. With MMM-VNDN, we change the default term of Face on ndnSIM to MAC ad-dress to identify the node. MAC address of neighbor is tracked in the flood phase and be sent by broadcast-to-unicast switching in second phase.

In case of our proposal, we assume that the VI table is already built up by captured images taken by camera. Following our design, we imitate a sequence of hop-hop forwarding based on VI table by pre-defining a path from Consumer to Producer. We can use this way to estimate packet overhead in our proposal.

Simulation Results for One-way scenario

Control packet overhead

The number of control packets is proportional to the numbers of nodes and times, we can confirm the total beacon SUM of n nodes in t seconds with rate m packets/s by following formula:

$$SUM = n \times t \times m$$

Figure 4.14 plots the result of total control packet generated in 200 seconds simulation time with m =1 then SUM is n × 200 × 1. Our proposal and MMM-VNDN method use FIB table for decision thus the control packet is zero.

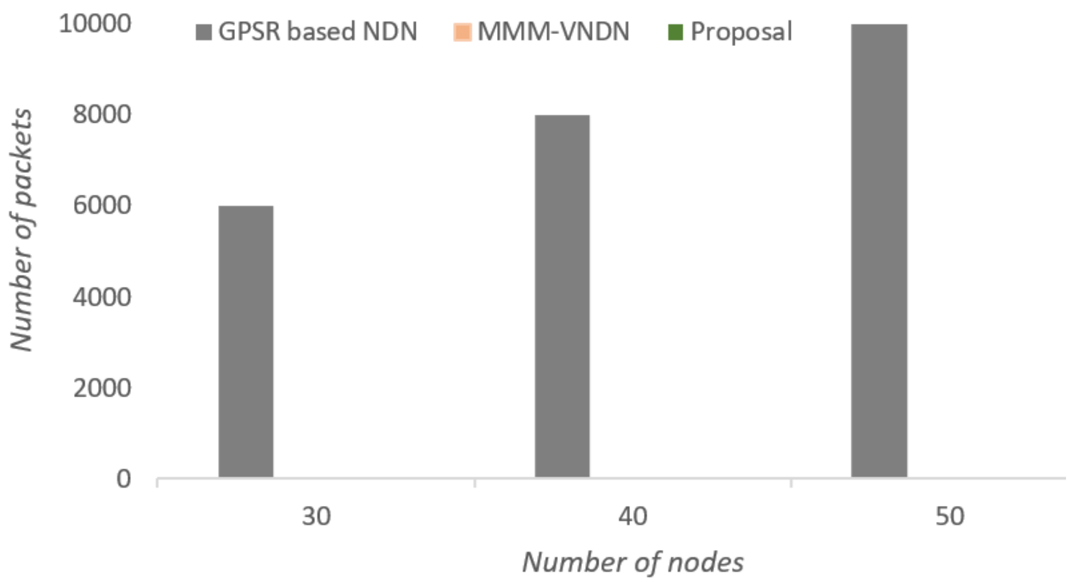


FIGURE 4.14: Number of routing control packets.

Interest Overhead

The total Interest includes the content discover Interest, recovery route Interest and retransmit time out Interest. In the same conditions, to prevent the redundant of Interest for the same content, we set Interest rate is 1 packet/s on our simulation. The result on Figure 4.15. shows that MMM-VNDN is much higher than the others, the reason is MMM-VNDN has first flooding phase when Interest is rebroadcasted by all the nodes. Moreover, when the path to Producer was broken as explained in setting section above, MMM-VNDN costs re-transmit packets and another flooding phase for route recovery.

GPSR based NDN and our proposal show the better result and consistent due to do not have any flooding phase, also in order using beacon and check before transmit mechanism to deal with broken link. We know that such pure FIB based forwarding method like MMM-VNDN suffers when the topology changes.

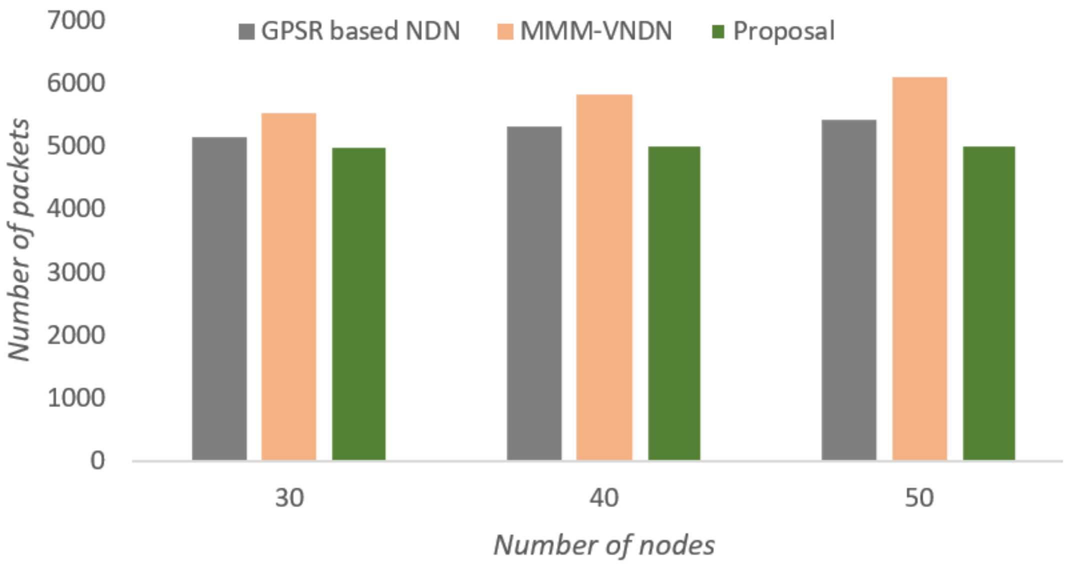


FIGURE 4.15: Number of Interest packets.

Total transmitted Packets

Total transmitted packets are the total number of Interest, control packet and data packet are plotted in Figure 4.16. In contrast to the previous good performance in the aspect of Interest overhead, GPSR based NDN generally sent highest traffic into network. The reason is GPSR based NDN method have to trade off a large amount of control packet to keep network link always on (capable of sending an Interest to the next-hop immediately).

Although the number of Data packets increases with the number of Interest and the number of nodes (flooding phase), MMM-VNDN still have better result than GPSR based NDN because this method maintains a FIB table.

We can see that our method transmitted the less traffic to retrieve the content, according to the goal of design, it clearly shows the advantage in packet cost overall.

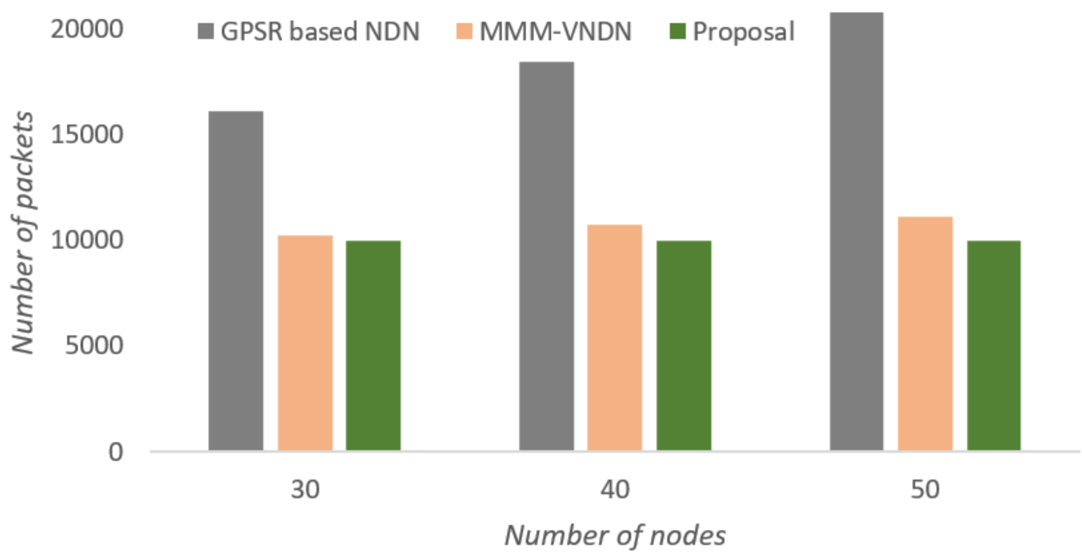


FIGURE 4.16: Total transmitted packets.

Interest Satisfaction Ratio (ISR)

The result of ISR of three methods are plotted in Figure 4.17. Although the GPSR based NDN and our proposal achieve similar values over 0.98, our method shows better result with low overhead. This indicates that these two methods are suitable this kind of scenario. Due to the broken link setup, MMM-VNDN suffer an amount of Interest to resend and recover FIB entry that effect the result ISR above 0.8.

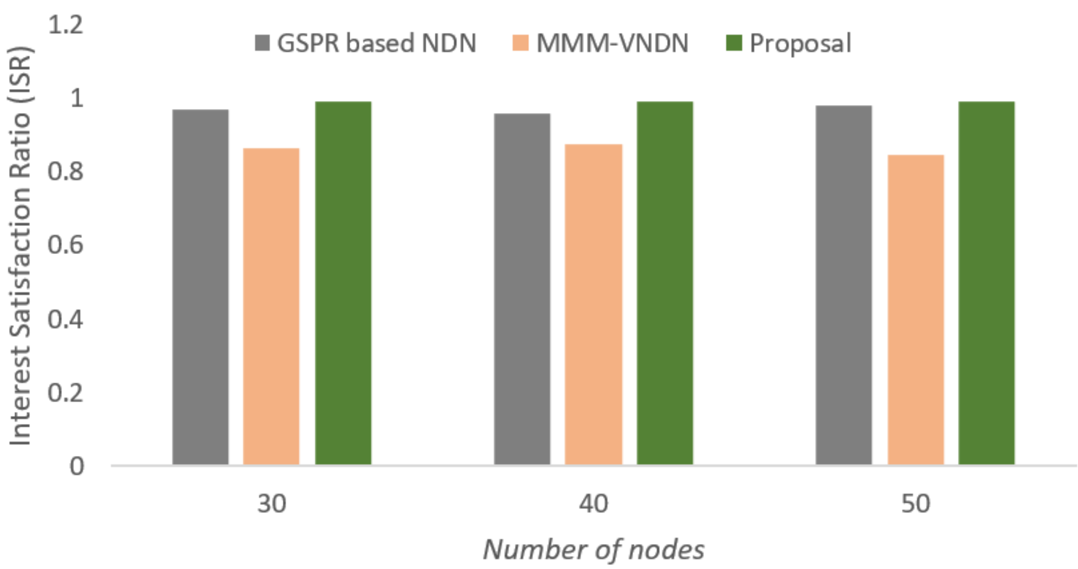


FIGURE 4.17: Interest Satisfaction Ratio (ISR).

4.3.2 Low density Two-way scenario

In case of two-way scenario with low density, we want to evaluate the impact of moving direction to the V2V communication in VANET.

Simulation Setting for Low density Two-way scenario.

The aim of this experiment is evaluate the effect of movement direction (opposite forwarding issue) on VANETs for each method. We setup a Consumer at the beginning of the road area periodic sends Interest along the road to the opposite Producer at the end of 1000 m road. If node density in both directions is the same, in many cases Consumer will chose the path in the same directions and forwarding behavior is similar to previous scenario, it makes the effect of opposite direction is not clearly identified. Thus, we assume that the node density in Consumer direction is much lower than the opposite side to increase the chance of forwarding message to opposite direction side and estimate the packet loss and delay due to opposite movement issue as shown in Figure 4.18 . We also compare the performance evaluation of the effect of using improving line in sight function (Proposal-Vision) that mentioned on previous section with the normal one in this scenario.

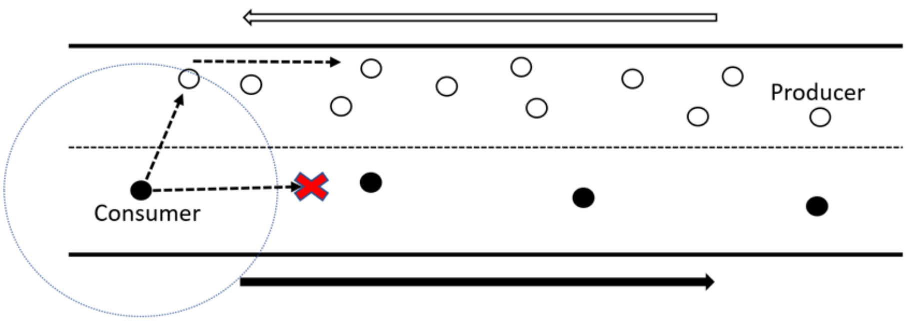


FIGURE 4.18: Low density two-way scenario.

Number of vehicles varying from 15, 20 and 25 that includes constant 5 nodes in Consumer's direction side and the rest on the opposite side. Table 4.7 shows the configuration settings for the following set of experiments.

TABLE 4.7: Simulation parameters for low density Two-way scenario.

Parameters	Detail
Number of Vehicles	15, 20, 25
Mac Protocol	802.11a 5GHZ
Transmission Range	100 m
Velocity	30 - 40 km/h
Transmission Rate	1 packet/second
Simulation Time	60 seconds

In this scenario, we use three metrics to evaluate all methods:

• Interest Satisfaction Ratio (ISR): Indicates the number of received-Data of Consumers divided by the total number of sent-Interest packets by changing the number of nodes on the side of the producer.

• Hop-count: The total number of intermediate nodes from Consumer to Producer and the return way (Successfully delivered Interest).

• Average Latency: This metric obtained a round-trip measurements by the average time taken from the time the Consumer sent an Interest message to the time Consumer received the return Data message.

Simulation Results for Low density Two-way scenario.

Interest Satisfaction Ratio (ISR)

The Figure 4.19 shows the Interest Satisfaction Ratio of all methods. GPSR based NDN has over 80result due to the impact of opposite direction. Even some Interest packet is lost due to be forwarded to the serial of nodes in opposite direction, GPSR still shows a good performance in such a low density scenario. The reason of MMM-VNDN is a flat-forwarding protocol that does not have any information of movement, MMM-VNDN has to recover the route every time the route is broken when the opposite car passed, it happens more frequently in two-way scenario makes MMM-VNDN has to send amount of res-transmission packet into network and shows only over 0.7 of ISR result. In the other hand, our Proposal has a real-time pre-checking before transmit mechanism that the packet is sent only if the next-hop is detected. Thus, the result of method when using improving line of sight function or not is does not change, and in addition due to the capability to recognize the direction of Vehicle by camera, our Proposal shows the good performance about over 0.95.

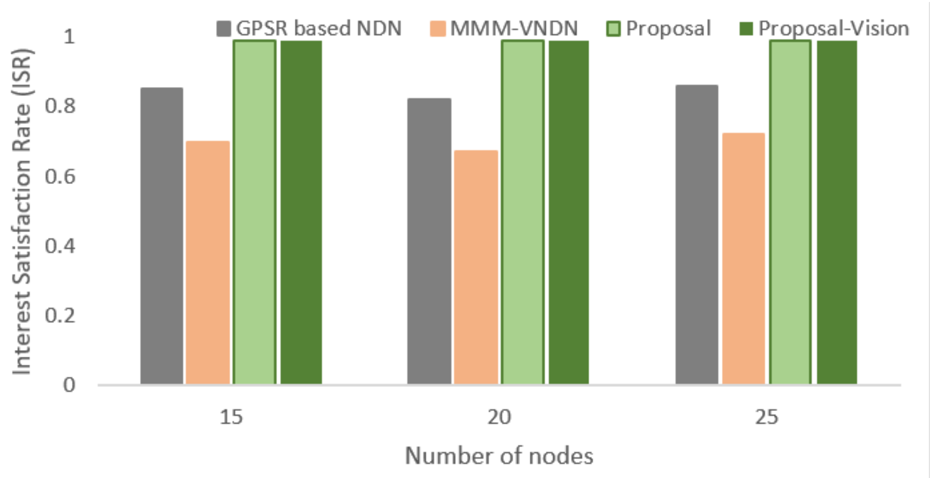


FIGURE 4.19: Interest Satisfaction Ratio (ISR).

Hop-count

The Figure 4.20 shows the number of hops for each 5 seconds when total number of vehicles is 25. The hop-count is coming down by time from 20 to 2, the reason is in our setting the Producer is opposite direction to the Consumer, by time the Consumer is moving closer to the Producer. We can clearly see that MMM-VNDN has the highest hop-count compare to other two methods. MMM-VNDN does not update the new route which has fewer hop-count even when the current next-hop passed through in the opposite, MMM-VNDN always stretch out the hop-count until the link is broken. GPSR based NDN and our Proposal-Vision shows the similar result, based on the position information the new route is updated frequently and the hop-count metrics is decreased by time. We can see the efficient of line of sight function on this metric, our default method shows a much higher hop count compares to visioned-method.

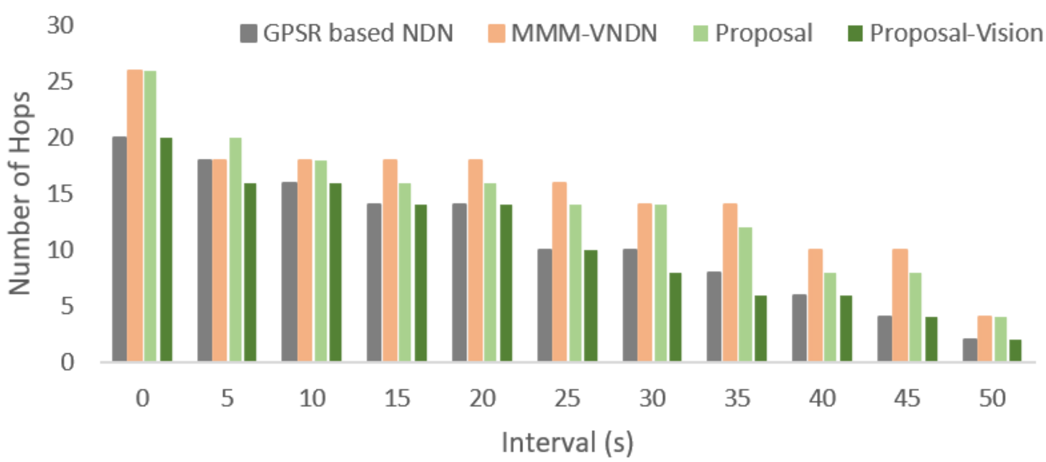


FIGURE 4.20: Hop-count in case 20 Vehicles.

Average Latency

Average Latency metric concerns to the previous hop-count metric, despite of good result in Hop-count metric, GPSR based NDN shows the highest delay result as shown in Figure 4.21 (7 ms to over 8 ms). The reason is the method we used to implement GPSR on ndnSIM, as explained in previous section we use UDPFace on ndnSIM 1.0 to simulate a IP-based methods, the Interest/Data message is encapsulated inside an UDP packet costs the time to process the packet over TCP/IP stack. In case of 15 nodes, Our normal Proposal and Proposal-Vision shows the same result because of our setting in sparse network with two-lanes for one side, node can clearly see the running ahead car that the improving ling of sight function is not effect. On the other hand when the number of nodes increases to 20, 25 the Proposal-Vision shows a better performance due to smaller hop-count around 4 ms compares to 5 ms of normal Proposal. Finally, MMM-VNDN has the highest hop count leads to a high delay.

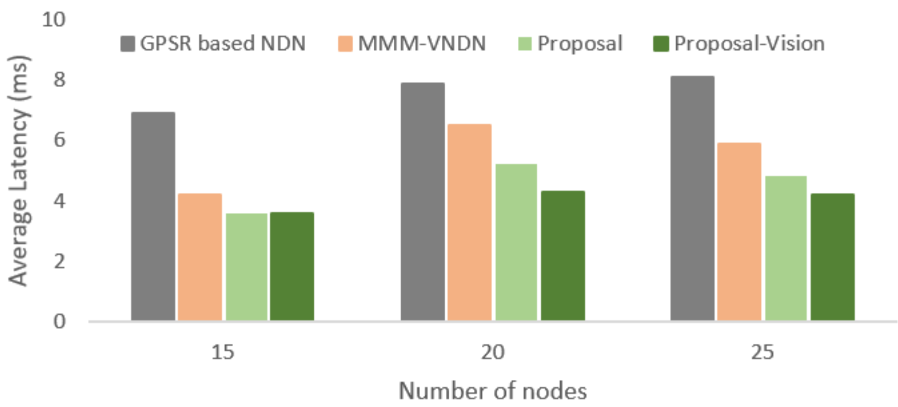


FIGURE 4.21: Average Latency.

4.3.3 High density Two-way scenario

High-density scenario is a typical natural vehicle traffic, we want to evaluate the impact of caching and the number of consumers to the V2V communication in VANET.

Simulation Setting for High density Two-way scenario

The aim of this experiment is evaluate the effect of caching and number of consumer for each method. We setup a the same condition with low density scenario where consumer at the beginning of the road area periodic sends Interest along the road to the opposite Producer at the end of 1000 m road. In this scenario the density of both ways is the same with velocity is set from 40 to 50 km/h, the number of vehicles is fixed to 40 and the number of consumers is varied from 2, 4, 6 that request the same content to evaluate the effect of cache compares to non-caching method (NDN based GPSR). Table 4.8 shows the common configuration parameters for the following set of experiments.

TABLE 4.8: Simulation parameters for High density Two-way scenario.

Parameters	**Detail**
Number of Vehicles	40
Number of Consumers	2, 4, 6
Mac Protocol	802.11a 5GHZ
Transmission Range	100m
Velocity	40 - 50 km/h
Transmission Rate	1 packet/second
Content Store	Least Recently Used (LRU)
Cache size	1000 packets at each node
Cache Policy	Leave Copy Everywhere (LCE)
Simulation Time	60 seconds

In this scenario, we change the number of consumers with requesting the same content to calculate some following metrics:

- Total number of Interest packets originated from original consumers.
- Total number of Interest packets transmitted from consumers (including retransmissions).
- Total number of Data packets received by Consumers.
- Total number of forwarded Interest packets by all nodes.
- Total number of forwarded Data packets by all nodes.

Simulation Results for High density Two-way scenario.

Numbers of packets actually sent and received by consumers.

Figure 4.22 shows the results of previous mentioned three features in order. Due to the affect of node movement explained from previous evaluation, When the number of consumers is 2, the actually sent Interest of NDN-based GPSR (4.8) and MMM-VNDN (3.7) is much higher than the originated Interest. When the number of consumers is changed to 4, 6, in case of GPSR, GPSR has the position information of neighbors and due to new consumers is nearer to the Producer gradually, GPSR prevents the transmit back to the running behind nodes that causes packet loss and show better performance (from 4.8 to 3.1 and 2.9). On the other hand, the number of Interest increases with the number of consumers in case of MMM-VNDN, MMM-VNN has no clue about position that the consumer in the middle position will send Interest into any directions on the flooding phase that increase packet loss and required more re-transmissions (6.2 and 8). Due to trade off amount of Interest packet, MMM-VNDN shows a better performance than GPSR in the number of DATAs, GPSR is suffered by the opposite movements flow due to not using PIT on the DATA return. Our both normal Proposal and visioned Proposal have the check before transmit mechanism and maintain next-hop on real-time that shows the best performance about 0.98 on both Interest and Data.

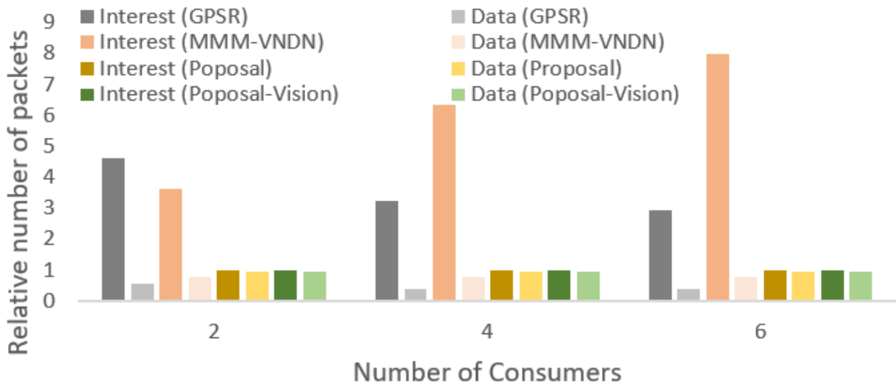


FIGURE 4.22: Numbers of Interest packets actually sent from consumers and Data packets received by consumers (normalized by originated Interests; changing number of consumers).

Numbers of Interest and Data packets forwarded by all nodes.

In Figure 4.23, in case consumer is 2, MMM-VNDN shows a worst result on both Interest and DATA due to the amount of traffic for flooding phase and recovery phase. However when the number of consumer is increased to 4 and 6, our proposal and MMM-VNDN give a similar tendency of decreasing overall due to the effect of the cache. By using IPFace, intermediate nodes of NDN-based GPSR not able caches the content leads to the number of packets increasing with the number of consumers. The results shows that our proposal also works on high density network, caching is effective in this evaluation and the benefit of NDN based protocol compares to IP-based method without caching. Due to the reducing hop-count of visioned-proposal, the results shows that improving line of sight for camera function is effective for mitigating the traffic on entire network.

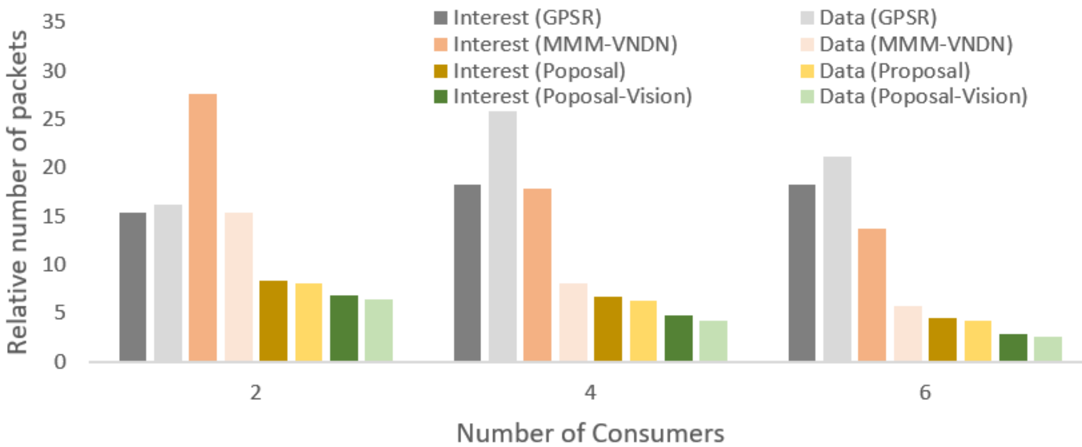


FIGURE 4.23: Numbers of Interest and Data packets forwarded by all nodes (normalized by originated Interests; changing number of consumers).

4.4 Discussion

Broadcasting on VANETs

Our protocol is designed based on pull-based of NDN architectures which contrast to the push-based of traditional network architecture. On VANET, on the side of driver, pull-based is suitable for system that helps driver maintains the content ahead by keep sending Interests along the driving route. In contrast to V-NDN, many previous works of IP-based network commonly uses broadcast-based forwarding (push-based) that increase the chance to reach all nodes as fast as possible on many emergency cases (emergency breaking or accident). Thus, based on the advantages of simplicity, We believe that a addition pushed-based is needed in our design but it has to be considered carefully because of two reasons:

First, as explained on previous chapter, broadcast is the most popular method to improve the chance of disseminating to all destinations but causes redundant traffic. The reason is due to the movement of the vehicle, in many cases the received broadcasted information is no need. For instance, the accident occurs only on one-way of road but the other direction of vehicles are running normally, in this case only vehicles that toward to the accident area are supported to receives this accident alert, when the rest of vehicles (opposite way and running head vehicles) receives and rebroadcasted without control (e.g. one-way broadcast) this alert leads to unrelated information is spread out to network more wasteful.

Second, on our design, the pull-based communication will be effective for multi-hop communication to reduce the number of packets. Our proposal is designed for checking the road information ahead following pull-based of NDN architecture, we recommend vehicles have to periodically send Interest to gather information ahead actively, combining with benefit of caching helps to disseminate information to more nodes more effectively without needless broadcasting in many cases. Broadcast is only effective to the limited vehicle near by the accident point because a periodical information may not reach by the deadline of driver's reaction such as change the lane or breaking control. In addition, area that broadcasting effectively work should be restricted in only a few hops and not to be spread all over network. Thus, in emergency case one-hop or two-hop broadcast (a push-based) can be incorporated with our design to forward critical alert as fast as possible and based on benefit of using front and rear camera, we also can control the broadcast forwarding direction (only vehicles are running toward to) or area (only vehicles on the same lane) to prevent broadcast storm problem.

Adapting to real world scenario

On this research, we focus on a protocol for application which supports road condition checking system where application periodically sends Interest along the road. Thus, our scenario we use to implement our design is a simple long road with one or two-way that not fully similar to the real-world road such as the lacking of road junction.

We can simply assume a real-world road contains various sets of connected junctions, the vehicle moves between junctions, not only a straight way and may changes the direction once arrives each junction, thus, how to keep the important content longer and distribute to any directions at junction will be considered as our future work. More complex scenario requires addition features for our design, e.g., we can combine the DTN and floating content protocol [93] to our design to improve the performance in content delivery on junction as following.

First, DTN as explained on chapter 2, is a protocol where node keeps and passes the packets only when encountered other node that supports high-delay content and suitable for any scenario especially sparse network. By using DTN, we can keep the popular or be re-used further content on network to expand the chance of disseminating to desired nodes and forward packet in any direction at will.

Second, we also can use floating content mechanism to control packet flow on each junction. The concept of floating content is disseminated opportunistically and desired node cache this content within anchor-zone, by this way content can be kept locally and reduce the chance of content disappears from network.

Credibility of simulation

In case of VANET, similar to MANET, the gap between simulation results and testbed is not too large. Authors on [105] evaluates the accuracy of Vehicular channel models (VCMs) be used on various simulators with field operational test (FOT) of real world on vehicle-vehicle (V2V) communication and DRSC-based testbed. The results proves that VCMs estimates the average of the frequent packet error rate observed in the FOT data though has a little over-estimate Inter-Packet (GAP) lower 10 percents and underestimate consecutive reception run-length (CRRL) and delivery ratio (3 percents) but still have similar tendency.

In case of obstacle shadowing, although our VANETs protocol is a line-of-sight transmission by using camera to identify the destination, thus it can encounter the problem of obstacle and we believe that addition of obstacle shadowing into our modelling for more scenarios is needs a our future work.

4.5 Summary

In this chapter, we proposed a new visual-identification based approach of Interest forwarding in Vehicular NDN network.

Due to lacking of node identification to encounter duplicated Face problem in Wireless Environment on RQ2, we introduce a new node identifier called Vehicle Identifier (VI). The concept of VI is obtained by taking advantage of front rear camera to capture the specification such as license number plate, color, car type, etc. of running around vehicles, then identify and assign the visual identifier (VI) to each node. Due to this active approach, it makes vehicle maintains all the neighbor nodes in VI Table easily. Furthermore, by camera VI includes the information of direction moving helps the forwarding process eliminates the movement problem on VANET.

We also provide a full unicast forwarding to address the RQ1 by improving the Next-Hop selection process by using VI Table and reconstruct FIB table and PIT by adding visual information as metrics for selecting process. Node has the best distance metric be elected as the candidate node and promoted to Next-hop or Requester field of FIB/PIT when an update or recreate of entry is needed. In this way of Next-Hop selection process, our method does not require extra message such as beacon message or flooding based route discovery message.

To encounter the dynamic mobility of VANET, We introduce a check before transmit mechanism to prevent the unreachable problem of VANET. Node process an message in step of using FIB/PIT have to check the available of entry by VI Table before send it out. An entry is good only if the candidate node is still on VI table and has the best metric or a new one will be selected.

In Performance Evaluation, we compare our method with GPSR based NDN (a typical beacon-based method) and MMM-VNDN (a pure NDN method) in three scenarios. The results of the performance evaluation show the followings.

• In One-way scenario, when the total number of vehicles increases, the result showed that the proposed method always requires the less amount of packet and in every aspect of overhead and good delivery ratio than GPSR based NDN and MMM-VNDN.

• In Two-way scenario with low density to evaluate the impact of opposite direction forwarding, when the total number of vehicles increases and the opposite direction makes connection in VANET more weaker, our proposal still shows a good performance in term of delivery ratio, delay and hop-count.

• In Two-way scenario with high density to evaluate the impact of cache and number of consumers, when the number of request is higher our proposal still showed a good performance compares to two other methods that costs much more traffic to discover content and recover the route, we also see the benefit of caching in aspect of packer overheads when compares to non-cache method.

These results shows the effectiveness of the proposed method compares to a typical beacon-based method that skipping all NDN architectures of FIB and PIT and uses only position information, and a pure NDN based method uses MAC-Address as node identifier to communicate.

Chapter 5

Conclusion and Future Work

5.1 Main Contributions

In this thesis, we studied on how to implement NDN paradigm to Mobile Ad Hoc Network, and proposed two methods to mitigate the redundant traffic of content delivery process (RQ1) and broadcast traffic of FACE logic problem of NDN architecture (RQ2) for both MANETs and VANETS. Table shows the research question and our solutions to deal with.

Hybrid NDN based Ad hoc Routing is a hybrid protocol that combining reactive and proactive routing for local-area content on public network on MANETs such as shopping malls, museum or park etc. In this typical content distribution services, the moving nodes of and fixed nodes are coexisted and content is reused frequently. In case of moving node has the role of the requester, node moves around a specific area freely, the number of nodes is high but the connection between nodes is unstable. On the other hand, fixed node such as server or wireless router has a role of provider, has less number of node but the connection is stable. To address the RQ1, We develop a design of hybrid approach routing protocol adopts the advantages of both proactive and reactive approach. Furthermore, we aim to reduce the burden for all the requester every time retrieves a content by dividing network into the producer side and the consumer side. Producer side includes location fixed devices. On this side we offer a proactive routing based focuses only on the name prefix advertisement due to the stable network and power of resources. Producer generate a directed a cyclic graph (DAG) individually to advertise its content. Information of content is shared and updated among producer side frequently. On the other hand on the consumer side, the mobile nodes such as smartphones do not use any method to populate the routing information, consumer side acts on reactive-based routing that request content only when needed. The FIB entry is built according to the first Interest packet for content discovery phase and flooded throughout the consumer side until it arrives some node belongs to the producer side, and the Interest will be forwarded to original Producer. After that, while the Data packet returns, a set on FIB entries indicate a path to Producer side is created on Consumer side nodes concurrently. This FIB also be used in future for following Interest of same content. The RQ2 is addressed in hybrid NDN by the way we utilize MAC Address to replace FACE notion. In our design, FIB and PIT table work correctly by adding MAC address to distinguish each node, since packet passes on intermediate nodes, the MAC address is always captured and stored to maintain a connection between nodes for routing purpose. We give a detailed description of the proposed mechanism with theoretical analysis in case of fixed nodes and simply moving nodes and we also provide a detailed way of implement NDN architecture to wireless ad-hoc network over NDNsim simulator and simulated 3 performance evaluations where node moves around of the random walk type. The results of the performance evaluation shows that the our proposal has good result in both traffic cost and delivery ratio metric compares to reactive method (REMIF) and proactive method (TOP-CCN).

Visual Identification based forwarding is applied for the case of MANETs is VANETs where the vehicle has much more faster velocity but the movement is predicable and more powerful resources in aspect of transmission range, equipment and computing. In VANETS the safety information is the most critical content that should be updated periodically leads to the cost of network traffic. Thus, we also consider this typical high dynamic scenario as a special case of MANETs research. In contrast to MANETs, the idea of maintain the content for whole network in proactive approach is impossible due to the fast topology change. Hence, to address the RQ1 and RQ2 in case of VANETs, we provide a lightweight and robust protocol for vehicular network by a receiver-based approach (reactive). For RQ2, instead of using MAC address or Node ID on beacon-based approach, our design leverages on front/rear cameras to identify a new identifier of node based on visual information such as number plate numbers (highest priority) and extended factors like color, brand, type etc. named visual identifier (VI). We design a lightweight way forwarding all in unicast-based to answer the RQ1 by the way node determines the VI of receiver by camera and also includes its VI into packet for the return way. Vehicle does not rely on beacon and able to choose the next-hop among all neighbors on the line of sight. In addition, to improve the accuracy of routing and forwarding, for instance due to the topology change, receiver is out of range while sending message that leads to packet loss, we also introduce a mechanism named check before transmit by keep monitoring the state of running around nodes in real-time. Every time before sending any packet, node has to observe that the current next-hop is still in line of sight or not to prevent packet loss. In performance evaluation section, we use SUMO to generate the real vehicular moving and operate the NDN based communication via NDNSim. We evaluate several metrics of traffic, delivery ratio and efficiency of route recovery by varying three scenarios: one-way, two-ways with low density and two-ways with high density. The results shows that our method has the good performance in number of packets due to all unicast-based, high delivery ratio and fast route recovery by using real-time camera in both case of out-of-range node and opposite-moving node.

TABLE 5.1: Research Questions and Answers.

Question	**Solutions**	
	MANETs	VANETs
How to mitigate the broadcast transmission on content delivery in MANET	We develop a hybrid approach that combining proactive and reactive protocol, it helps to reduce the burden of content discovery for the consumer	We design a all unicast communication for VANETs by using VI, we also eliminate the flooding phase for first content discovery and route recovery on NDN.
How to mitigate the broadcast transmission on FACE logic problem of NDN	We introduce a MAC-Address to FACE mapping solution to make NDN communications works in unicast manner	We propose a new Node Identifier called Visual Identifier (VI) based on visual information captured from camera, VI is maintained in a active way to create unicast communication.

5.2 Future Work

Although in this thesis we studied on implementing NDN on Mobile Ad Hoc Network and we proposed two methods to mitigate the traffic overhead on content dissemination, the following points of further investigation in respect of routing and forwarding will be addressed in our future works.

• On Mobile scenario, although our method is designed and the performance evaluation was shown that is suitable for local content dissemination application, a extension of this design supports for much larger scale of network is required. The motivation of this extension is improving the performance for each side of network by associating with more other routing protocol approaches especially on the consumer side where we only used a simple reactive based routing. Furthermore, with the development of mobile network, the multi-interface mobile devices become more popular that able to operate V2V, V2I and also cellular network communication in parallel, a scope of content from multi-consumer increases as an issue and a fast/dynamic for interface selection mechanism is required for all future protocol designs.

• On Vehicular scenario, on this design we used the NDNSim version 1.0 to take advantage of the IPFace function to implement a NDN-based traffic for a IP-based method (GPSR) for performance evaluation purpose. However, NDNSim version 1.0 does not support the WIFI 802.11p commonly used for Vehicular network, an performance evaluation of comparison for two WIFI models with a more large scale of network is required. Second, in the aspect of efficient and effective that our method is a lightweight method that operating a full unicast communication for nodes, however with more complex or similar to the real world scenario, re-modelling simulation setting and improving the content distribution process is important and still are open challenges. Finally, due to the special characteristic of VI, in case such as due to the bad weather or car accident, our design maybe becomes not able to work correctly, we need a modification for our method such as that capable to incorporate with any NDN-based Mobile ad hoc network protocols which uses Node name or MAC address and etc. as a Node Identifier as an optional on the future.

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