Information-Centric Networking based Caching and Naming Schemes for Internet of Things: A Survey and Future Research Directions

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Abstract—Information-Centric Networking (ICN) is being realized as a promising approach to accomplish the shortcomings of current IP-address based networking. ICN models are based on naming the content to get rid of address-space scarcity, accessing the content via name-based-routing, caching the content at intermediate nodes to provide reliable, efficient data delivery and self-certifying contents to ensure better security. Obvious benefits of ICN in terms of fast and efficient data delivery and improved reliability raise ICN as highly promising networking model for Internet of Things (IoTs) like environments. IoT aims to connect anyone and/or anything at any time by any path on any place but some IoTs like smart phones may not. From last decade, IoTs attracts both industry and research communities. IoTs is an emerging research field and still in its infancy. IoTs foremost target is to connect efficiently billions of things in a way to reduce human involvement in the operation of machines. While IoT wild-deployment puts many challenges, among others, one challenge is how to address efficiently so many heterogeneous and constraint-oriented devices. Thus, this paper presents the promise of ICN for IoTs by providing state-of-the-art literature in this context. We provide IoTs major components involved during its life-cycle and list required features for IoT network architecture. We present major ICN architectures and their applicability for IoTs. We survey ICN based naming and caching approaches for IoTs with appropriate classification and furthermore present OSs and simulators for ICN-IoT. We also provide important research challenges and issues faced by ICN for IoTs.

Index Terms—IoT, ICN, NDN, CCN, Information-Centric Networking, ICN-IoT Caching Schemes, ICN-IoT Naming Schemes, Taxonomy.

I. INTRODUCTION

A. Motivation and Background

IoTs aim to connect each and every device with the Internet, so that these devices can be accessed at any time, at any place and by any path (i.e., from any network) [1]. IoTs canopies enchanted objects like smart washing machines, smart refrigerators, smart microwave ovens, smartphones, smart meters and smart vehicles. Connectivity of these smart objects with the Internet enables many valuable and remarkable applications like smart home, smart building, smart transport, digital health, smart grid and smart cities. When billions devices connects to the Internet, generation of large amount of data is an apparent consequence. Besides that, this data combines with the data that produces through, for instance Facebook likes and Youtube videos etc. Thus efficient data discovery and access put more constraints on the underlying TCP/IP architecture and eventually raises many issues.

Among these, from device perspective, one is naming and addressing every device [2]-[3]. As IPv4 addressing space is exhausted, IPv6 address space may also exhaust in future. In addition, IPv6 address is long and it is less suitable for communication through processing power constraint-oriented devices like wireless sensors [4]-[6]. Therefore, efficient naming and addressing schemes for billions of devices (and contents) are not ideally available in IP-architecture. On the other hand, every device has different specifications and constraints raising another issue of heterogeneity. IoTs comprises on heterogeneous devices and most of the devices are tiny, low power, limited memory, low cost and constraint-oriented wireless sensors. These devices are usually known as smart devices. Due to low memory and low battery life, data can become unavailable most of the time. Thus solutions like in-network caching and issues faced by ICN for IoTs.

Moreover, some IoTs applications, for instance, VANETs, MANETs and smart transport requires better mobility handling [8]-[9].

From data perspective, mostly IoTs application users are more interested in getting the updated information rather than knowing the address of information source. For instance IoT devices, especially in the domain called wireless sensor networks (WSN), have specific purpose to harvest information and at the large scale [10]. Every device has to perform some specific task, for example temperature sensors measure temperature from their surroundings and does not perform word processing task that a general purpose computer does. Any user of temperature measurement application is interested in current temperature of a certain area instead of the temperature value of a specific sensor. To fulfill these above mentioned requirements and due to recent trends about IoT architecture have prompted many research organizations to initiate multiple projects. Therefore many evolutionary (or dirty slate) approaches are being explored for IoTs, for instance IPv6 based 6LoWPANs [11]-[12]-[13].
Among these, most of the projects are working under Internet Engineering Task Force (IETF). IETF projects are designing protocols for constraint-oriented devices based networks. The Constrained RESTful Environments (CoRE) group designed a framework for smart applications to work efficiently on IPv6 based constraint-oriented smart devices. Constrained Application Protocol (CoAP) is a major achievement that accomplished under CoRE working group. CoAP is a lighter version of HTTP protocol. It is mainly designed for low power devices forming constrained networks. CoAP also supports various caching forms that was mentioned in REpresentational State Transfer (REST) protocol. CoAP runs over UDP to provide better communication among resource-oriented devices. IPv6 over Low Power Wireless Personal Area Networks working group (6LoWPAN-WG) has focused on 6LoWPANs. This group works for adaption of IPv6 over IEEE 802.15.4 based networks. 6LoWPAN group also works for IPv6 header compression to efficiently run over low power devices. Routing Over Low power and Lossy networks working group (ROLL) mainly focuses on developing routing strategies and self-configurable mechanism in low power networks. Low power and Lossy networks (LLN) made up of many embedded devices which include limited power and memory devices. LLN provides an end to end IP based solution for routing over these networks. 6LoWPAN-WG will work closely to ROLL. Sometimes situations can happen in IoT when constraint-oriented devices are required to communicate with each other without any gateway. Therefore, IETF has designed IPv6 Routing Protocol for Low-Power and Lossy Networks (RPL) for communication between constraint-oriented devices. RPL provides support for point-to-point and multipoint-to-point and point-to-multipoint traffic patterns. Further, the Light-Weight Implementation Guidance (LWIG) working group is focusing to build minimal and inter operable IP protocol stack for constraint-oriented IoT devices. And the Thing-2-Thing Research Group (T2TRG) aimed to explore the factors that will influence the process of turning IoT into reality. T2TRG will investigate and list the issues to form the internet through which low power constraint-oriented devices can communicate to each other using M2M communication style and with the global Internet. Moreover, the European Telecommunications Standards Institute (ETSI) is working on the standardization of data security, management, processing and transport for IoT on the basis of IPv6. However, more details about IoT projects and protocols can be found on.

Nonetheless, above mentioned projects for IoT architecture lies under ‘all-IP architectures’ umbrella. And IP-based networking is inherently designed for host-to-host communication where location (e.g., address) of host plays a vital role, but this location-dependent design creates certain bottlenecks such as efficient information retrieval and delivery. Also, IP networking requires additional protocols to support privacy and security of sensitive data, scalability, mobility and heterogeneity of nodes. Consequently, traditional IP-based networking is less suitable for these IoT devices and applications. Hence, to provide efficient connectivity among low power IoT devices, a novel networking model like ICN, holds much promise.

Due to this, IETF has also started ICN research group that will help to evolve IP-based architecture.

ICN is a promising candidate for the future Internet foundation. ICN primary characteristics include in-network caching, naming the contents, better mobility, improved security and scalable information delivery which are naturally suitable for IoT applications. So far, there are nine major architectures proposed under the concept of ICN including DONA, CCN, PURSUIT, NetInf, CURLING, CONET, MobilityFirst, C-DAX and Green ICN. Among these ICN based architectures DONA, SAIL, COMET and CONVERGENCE, CCN all are dirty-slate while MF, PURSUIT and NDN are clean-slate architectures. CCN (NDN) is prevailing approach among other ICN based proposed architectures. ICN based hourglass architecture provides us with thin-waist like TCP/IP. ICN mask over TCP/IP network layer or MAC layer is narrow enough to accommodate more devices or networks. Current literature argue that ICN seems to replace IP, rather we believe and foresee ICN as an overlay network sitting on IP network. In fact CCN is a layer that mask the need of associating content with the IP address instead by name. The actual content delivery still require TCP/IP interface or direct MAC (layer 2) interface. CCN could be applied just above MAC layer especially in WSN.

ICN’s striking feature in-network caching can handle efficiently the issue of information delivery from dead (unavailable) device due to low battery life by caching contents at intermediate nodes. Also it can minimize retrieval delay even in case of alive devices through the use of caching. While naming the contents can resolve the address space scarcity issue of IPV4 and can enable scalability in an efficient way. It also offers better name management and easy information retrieval of huge data produced by IoT applications. That’s why in this article we survey ICN based both naming and in-network caching schemes. Moreover, mobility handling provides better hand-off for mobile devices like mobile phones and vehicles. ICN’s self-certifying contents provide more security to data rather than securing the hosts. List of acronyms used in this paper is provided in Table I.

B. Review of Related Survey Articles

Our current survey on IoTs and ICN is unique from the prior surveys as we provide holistically ICN based caching and naming schemes for IoTs. A plenty of surveys is available on either IoTs alone or on specifically ICN related issues; though, to the best of our knowledge this work is the only detailed survey that emphasizes ICN for IoTs.

Exclusively IoT emphasized surveys have covered the IoT basics including building blocks and characteristics, enabling technologies, smart potential applications, projects and related research challenges in [2], [8], [10]. Eight research directions for IoTs are listed down in [6]. Context awareness solutions for IoTs are discussed in [38]. Middle-ware requirements and solutions are surveyed in [39]. IoTs security issues and their corresponding solutions are outlined in [40]. In [41], specifically Sybil attacks in IoTs are discussed along with
their defense schemes. Moreover, classification of Operating Systems (OSs) for IoTs is presented in [42]. List of survey paper for IoTs is provided in Table I.

Surveys that solely focused ICN include [34], in which general ICN is described along with four ICN architectures including DONA, CCN, PSIRP and NetInf. Further, George Xylomenos et al., in [35] described ICN concept, its features and extended the research in [34] by adding three more updated architectures named CONVERGENCE, CONET and MobilityFirst. Moreover [43] focused on ICN energy efficient caching schemes on the basis of content placement, cache placement and request-to-cache routing. While [44] discussed only NDN and DONA architectures, summarized caching mechanisms, described performance parameters and conducted simulations for the evaluation of caching mechanisms. Routing and naming schemes for ICN are covered in [45]. Comprehensive survey of possible attacks in ICN is presented in [46]. Moreover, taxonomy of security attacks (i.e. categorized into naming, caching, routing and other attacks) in ICN is presented and their existing solutions are discussed. ICN for VANETs along with future research directions is presented in [47]. ICN related literature is listed in Table I.

One pioneer short article [48] that identifies ICN for IoT, surveys briefly ICN for IoT without providing enough literature survey. In contrast to [48], our present survey, provides comprehensive up-to-date review of ICN for IoT, including ICN models and their feasibility for IoT, additionally caching techniques and naming schemes along with operating systems, simulators and detail research challenges for research community.

| Acronyms | Definitions                        | Acronyms | Definitions                        |
|----------|-----------------------------------|----------|-----------------------------------|
| 6LowPANs | IPv6 over Low power Wireless Personal Area Networks | BN       | Border Nodes                      |
| CCN      | Content Centric Networking        | CS       | Content Store                     |
| CR       | Content Router                    | CRS      | Content Resolution System         |
| CaR      | Content aware Router              | COMET    | Content Mediator architecture for content aware nETworks |
| CONET    | Content Network                   | CRN      | Cognitive Radio Networks          |
| DF       | Destination Flag                  | DH       | Dissemination Handlers            |
| DHTs     | Distributed Hash Table            | DONA     | Data Oriented Network Architecture |
| DoS attack | Denial-of-Service attack       | DPEL     | Dynamic PIT Entry Lifetime        |
| DPI      | Deep Packet Inspection            | FF       | Forwarding Function               |
| FIA      | Future Internet Architecture      | FIA-NP   | FIA-Nest Phase                    |
| FIB      | Forwarding Information Base       | FN       | Forwarding Node                   |
| FF7      | Framework Programme 7             | FSS      | Fixed Satellite Services          |
| GEO      | Geostationary Orbit               | GNRS     | Global Naming Resolution Service  |
| GPRS     | General Packet Radio Service      | GSM      | Global System for Mobile communication |
| GSO      | Geosynchronous Orbit              | GUID     | Globally Unique Identifier        |
| HEO      | High Earth Orbit                  | IERC     | IoT European Research Cluster     |
| ICN      | Information Centric Networking    | IN       | Intermediate Nodes                |
| IoT      | Internet of Things                | IPV4     | Internet Protocol version 4       |
| IPV6     | Internet Protocol version 6       | LEO      | Low Earth Orbits                  |
| LRU      | Least Recently Used               | LTE      | Long Term Evolution               |
| LTE-A    | LTE Advanced                      | M2M      | Machine-to-Machine                |
| MEO      | Medium Earth Orbit                | MF       | MobilityFirst                     |
| MIMO     | multiple-input and multiple-output| MSS      | Mobile Satellite Services         |
| NDN      | Named Data Networking             | NetInf   | Networking of Information         |
| NFC      | Near Field Communication          | NRS      | Name Resolution System            |
| NSF      | National Science Foundation       | ON       | Opportunistic Networks            |
| P2P      | Peer-to-peer                      | PARC     | Palo Alto Research Center         |
| PIT      | Pending Interest Table            | PLC      | Power Line Communication          |
| PSIRP    | Publish-Subscribe Internet Routing Paradigm | PURSUIT | Publish SUbscribe Internet Technology |
| RENE     | REndezvous NEwork                | RF       | Rendezvous Function               |
| RFID     | Radio Frequency Identification     | RH       | Resolution Handlers               |
| RID      | Rendezvous ID                     | RN       | Rendezvous Node                   |
| SAIL     | Scalable and Adaptive Internet soLutions | SID     | Scope ID                          |
| SIT      | Satisfied Interest Table          | SN       | Satellite Networks                |
| TCP/IP   | Transmission Control Protocol/Internet Protocol | TMF     | Topology Management Function      |
| TN       | Topology management Node          | UMTS     | Universal Mobile Telecommunications System |
| V2C      | Vehicle to Vehicle                | V2R      | Vehicle to Road side unit         |
| VANETs   | Vehicular Adhoc NETworks          | VDI      | Versatile digital item            |
| VIP      | Virtual Interest polling          | WSN      | Wireless Sensor Network           |

Table I

LIST OF ACRONYMS USED
Table II

**IoTs and ICN Related Survey Articles**

| Sr# | Reference(s) | Topics Covered | Publication Year |
|-----|--------------|----------------|------------------|
| 1.  | [39]         | IoT middleware requirements and solutions | 2016 |
| 2.  | [40]         | IoT security Issues and their corresponding solutions | 2015 |
| 3.  | [42]         | Classification of IoT Oss | 2015 |
| 4.  | [4]          | Eight research directions for IoTs | 2014 |
| 5.  | [38]         | Context awareness solutions for IoT | 2014 |
| 6.  | [41]         | Sybil attacks in IoTs have been discussed along with defense schemes | 2014 |
| 7.  | [10]         | Basics of IoT including building blocks and characteristics of IoTs, IoT enabling technologies, smart potential applications, projects and related research challenges | 2015 |
| 8.  | [5]          | Eight research directions for IoTs | 2014 |
| 9.  | [2]          | Basics of IoT including building blocks and characteristics of IoTs, IoT enabling technologies, smart potential applications, projects and related research challenges | 2015 |

**ICN Related Survey Articles**

| Sr# | Reference(s) | Topics Covered | Publication Year |
|-----|--------------|----------------|------------------|
| 1.  | [47]         | ICN for VANETs and Future Directions | 2016 |
| 2.  | [46]         | Taxonomy of security attacks and naming corresponding solutions | 2015 |
| 3.  | [44]         | ICN energy efficient caching schemes, content placement, cache placement and request-to-cache routing | 2014 |
| 4.  | [43]         | Seven ICN Architectures and Research Directions | 2014 |
| 5.  | [35]         | Routing and naming schemes | 2012 |
| 6.  | [45]         | Four ICN Architectures | 2012 |

**ICN for IoT Survey Article**

| Sr# | Reference(s) | Topics Covered | Publication Year |
|-----|--------------|----------------|------------------|
| 1.  | [48]         | Briefly identify ICN for IoT and Future Directions | 2016 |

### C. Contribution of This Survey Article

We aim to provide holistic and comprehensive literature on ICN based in-network caching and content naming schemes for IoTs. Besides from this, in this paper, we briefly provide IoTs basics including its life cycle, connectivity types followed by its architecture requirements. Then, we describe and illustrate ICN with the help of its distinctive characteristics and provide mapping of these characteristics with the formerly identified IoTs architecture requirements. After that, we discuss ICN models proposed so far and their suitability for IoTs. With such goals, to the best of our knowledge, it makes this paper pioneer and unique in this field. Furthermore, we outline the details of contributions we made:

- We provide IoTs related literature along with IoT processing cycle, its current and future enabling technologies, IoTs noteworthy applications and eventually, we identify important requirements for IoT network architecture.
- We provide an in-depth overview of ICN as well as its striking features.
- We provide mapping of ICN striking features against IoT network architecture requirements.
- We provide briefly major ICN based architectures and provide their comparison on the basis of selected characteristics.
- We provide comprehensive survey ICN based in-network caching techniques for IoTs and classification of these schemes on selected parameters.
- We provide classification of ICN based content naming approaches for IoTs.
- We provide issues, challenges and future research directions related with ICN based IoT.

### D. Organization of the paper

The rest of the paper is organized as follows. Section II provides a literature review about IoTs, its elements, characteristics and IoT network architecture requirements, basics of ICN and ICN models that have been proposed so far. In section III, we discuss and present state-of-the-art ICN-IoT node and network related literature. ICN based caching techniques for IoTs are discussed in section IV. Section V presents ICN-IoTs naming approaches. Section VI presents available OSs and simulators for ICN-IoTs. In section VII, we present open challenges and future trends of ICN into IoT. Finally, section VIII concludes the paper.

### II. Internet of Things (IoTs): An Overview

This section is presented with twofold purpose. Firstly, we present an overview of IoTs including background, basics and components involved in IoTs life cycle. Secondly, we list and describe resulting IoTs architecture requirements. However, our aim is not to survey and discuss IoTs in depth rather we illustrate it to highlight issues and identify architecture requirements. These IoTs requirements mapped against ICN striking features to show ICN significance for IoTs in the following section.
A. Brief Background

With the miniaturization and rapid production of smart devices in different domains like RFID and WSN caused their huge and frequent usage. Data that these smart devices collect is being shared and transmitted at an amplifying rate with the help of Internet enabled smart devices.

Eventually this trend of connectivity among smart devices with the Internet had born the concept of Internet of Things (IoTs).

B. IoTs Definitions

In 2010, authors of [2] defined IoTs as multi-vision paradigm that cover things oriented, Internet oriented and semantic oriented visions. This semantic oriented vision is the important one that exhibits the real power of IoTs. Moreover they state IoTs as a disruptive technology.

IERC [1] defined broadly IoT as global and dynamic network that can configure itself by employing interoperable communication protocols and things include both virtual and physical things that carry unique addresses along with physical and virtual features.

According to [3] IoT and smart environment involves devices that are referred by sensors and actuators. Through this perspective innovative applications can be developed that involves definitely information representation, data analytics, ubiquitous sensing with the help of cloud computing to form a unified network [3]-[49].

Thus IoT is introduced as a novel concept that is being supported by existing technologies. IoTs is manifold technology combining transport, health, building, industrial automation, environment, agriculture, RFID and personal sensors. Moreover IoT mainly consists of conversion mechanisms for data collected from smart devices into information though web of things to provide knowledge to us. And IoTs evolutionary process of correlative technologies involves: machine type communication (MTC) , WSNs, sensor web enablement, sensor web, web of things and semantic sensor networks [49].

C. IoTs Connectivity Types

As IoTs is the connectivity of things through the unified Internet. Things can be humans and smart machines of any sort. These things can connect in three ways: i) Machine-type-Communication (MTC), ii) Machine-to-Human (M2H) and iii) Human-to-Human (H2H).

- Machine-type-Communication (MTC) connectivity: This sort of connection occurs when a machine (object) wants to share its collected data to another machine or when a machine controls another machine. For example washing machine controller asks its buzzer to turn on or off when timer triggers. This MTC connectivity is the soul of IoT environment. MTC was formerly known as M2M connectivity. It fulfills main purpose of IoTs to automate the life of an individual to make it better. This broader connectivity can be further elaborated in following categories that actually involves this MTC connectivity.

- Machine-to-Human (M2H) connectivity: It happens either a machine has to deliver some important information or response of any query towards human or when human needs to connect with machine to control it. For instance when house owner enters the house, garage door confirms his/her entry by sending a message to the owner.

- Human-to-Human (H2H) connectivity: This way of connection is already in use where a human is connecting with other human to build and enjoy social relations. They share photos and every moment of their life with other humans. For this sake they need to connect with the Internet.

Moreover this is illustrated in the upper portion of Fig. [1]

D. IoTs Life Cycle and Corresponding Elements

Resulting IoTs life cycle and corresponding enabling technologies are shown in Fig. [2] IoTs life cycle involves usually four phases: i) Data acquisition and sensing, ii) Data transmission, iii) Data processing and information management and iv) Utilization in user applications and actions. These phases are briefly described below in following sub-sections.

1) Acquisition and Sensing: It defines the procedures to sense and collect data from IoT physical smart devices. RFID technology is used to identify tagged objects while sensor networks is utilized to sense data from smart sensors. To collect data, Zigbee or Bluetooth communication technologies are employed. Smart devices and sensors are therefore required to fully function IoT. Data that needs to be sensed may include temperature, proximity, speed, smoke, air flow and its direction, light and corrosion. Identification is collection of person’s identity that consists of name, age, national identity number or electronic product code (EPC) of any product. Sensors like camera, heat sensor and corrosion sensor perform data sensing. RFID readers identify and track tagged objects by accessing its EPC. Usually Bluetooth, Zigbee (IEEE 802.15.4), UWB and NFC are hired for data collection. RFID works better in tracking and identification applications while WSN has versatile applications and main component of IoT applications.

2) Data Transmission: It deals with communication and network technologies to transmit gathered data from sensors and tags through NFC or Bluetooth towards user applications. Thus techniques and technologies are required to deal heterogeneity (i.e., different kind of sensors, tags), addressing and naming for huge number of devices and contents (e.g., IPV6, ICN) and to support scalability of both contents and devices. Current communication technologies that fulfills this purpose include ethernet, wi-fi, wi-max, MANETs, cellular networks (3G/4G/LTE) and satellite networks. While future communication technologies and techniques include 5G, cognitive radio networks (CRN), vehicular adhoc networks (VANETS), power line communication (PLC) and ICN. Moreover, it can be seen in the middle portion of Fig. [1] that Internet technologies includes ethernet, Bluetooth, RFID, wi-fi, wimax, cellular (2G, 3G, 4G and 5G in the future), radars and satellites in the order of increasing range and power respectively. Thus by enabling IoTs, tremendous and smart applications are being achieved like smart individual, smart home, smart buildings, smart hospitals and smart transport (shown in lower portion of Fig. [1]).
3) **Data Processing and Information Management:** This phase deals with computation units and methods that process and analyze the data. Huge amount of data is being produced by IoT devices, therefore efficient methods are required like cloud computing and big data to manage and store data.

4) **Action and Utilization:** In this final phase, mechanisms are employed to utilize the processed data by forwarding data towards actuating applications. Those applications may provide different services like activity recognition of Alzheimer patients, detection of fire and setting it off through some actuator, detection of terrorist (or suspicious person) and alert guards. This is carried through AI, machine learning and semantic analysis.

These major IoT working phases and corresponding elements related literature is listed in Table. III.

### E. IoTs Architecture Requirements

Specific requirements and challenges [2], [10], [5] introduced by IoT network architecture outlined and given below:

1) **Scalability:** As IoTs envisions not only connecting networks and corresponding devices but enabling low power devices in billions to connect through Internet. Thus, it imposes new challenges over underlying architecture in terms of scalability. IoTs architecture needs to support billions devices in efficient way. Current solutions like IPV6 has huge address space that can serve IoT devices. Although in future, addressing the IoT devices is not the only issue. Another case is large amount of data that is being produced by IoT devices needs better and efficient scalability management. Therefore, there is need to explore IoTs network architecture in terms of scalability and it should be scalable to content access and network efficiency.

2) **Mobility:** Number of mobile devices connecting to the Internet exceeds the stationary nodes. Mobile devices like tablets, smart-phones have small screen and limited battery life. Some IoTs applications involves and requires anytime, anywhere connectivity, in which users want to check their emails and/or make calls at anywhere, anytime. To provide
fast, reliable connectivity and make data available at everywhere, network architecture should support seamless mobility and roaming.

3) Security and Privacy: As in some IoT scenarios like smart health and smart hospital; data that needs to be transmitted, is highly sensitive. If any hacker tries to change it, it can lead to alarming condition. To enable IoT efficiently, it should provide authorization, confidentiality and integrity. Standards are needed to specify the data access policies like who can access the data and who cannot. Take the example of smart home where the detail of pizza ordered by house owner is required by pizza shop to charge the payment. If this detail is shared to his doctor or insurance company, this can effect user privacy. As insurance company is not the tentative user could use the private data in wrong way. However privacy must be ensured via some access policies.

4) Naming and Addressing: IoT consists of billions of tiny, low-power, constraint-oriented devices which needs unique names or addresses to get recognition in the network. If we talk about a single nano-network which may contain thousands of nano-nodes and then interconnection of many nano-networks would require complex IDs or addresses. Although large address space is available in IPv6, it may help addressing and naming problem of IoT devices. But for constraint oriented simple devices it would be complex to process long address for a very small communications thus resulting the wastage of resources. Further IoTs contents being produced and processed at very fast speed. In addition these there can be many versions or values against any single content with different time stamps. Naming these rapidly produced contents is issue for IoTs. Thus energy efficient mechanisms are required to make data available with absolute certainty. Consequently, methods like in-network caching are required to make data available with absolute certainty.

7) Energy Efficiency: As obviously billions devices need huge amount of energy to build IoTs applications. Moreover, most of the smart devices are low in battery life such as wireless sensors. Thus energy efficient mechanisms are required to make this universal connectivity possible in the form of IoTs.

III. INFORMATION-CENTRIC NETWORKING (ICN)
OVERVIEW w.r.t IoTs

This section fulfills three purposes: Firstly, we provide a brief introduction of ICN concept along with its suitability for IoT. Secondly, we discuss ICN supporting IoT features and provide their mapping against IoT architecture requirements, and lastly we describe ICN based proposed architectures w.r.t their naming and caching feasibility for IoTs.

A. Limitations of TCP/IP and Importance of ICN for IoTs
As TCP/IP was traditionally designed to connect limited number of computers, to share limited and expensive network
resources with limited address space at network layer. And inherently it is not designed to fulfill IoTs requirements efficiently. Moreover IoTs huge data put additional requirements on the underlying architecture like data dissemination, security, mobility and scalability. In addition, flash crowds are the obvious consequence of today’s Internet usage [34], [35], [103]. [104], [105].

To solve IoT global connectivity efficiently, research community has started to propose different solutions to overcome issues of TCP/IP. As a result of these efforts, ICN is appeared as promising approach for IoTs [23], [46], [37], [106], [107].

In naive ICN, information is named independent from its location so that it can be located anywhere globally. Naming the data and devices makes ICN more suitable for IoT as it can combine billion of devices and huge information contents. Moreover, as IoT receiver of information is more interested in data rather than its location. ICN supports receiver driven communication making the communication under full control of receiver. Push type communication can be provided using beacon messages [108]. Further data can only be accessed whenever receiver explicitly requests a data. ICN offers in-network caching making it ideal for low power devices. Data is found on the basis of its location independent name. This provides opaque communication between sender and receiver making it more secure.

B. ICN Proposals Characteristics suitable for IoTs

In this subsection, we discuss and elaborate main features of ICN proposals to prove their worth for IoTs.

1) Named Data: Naming the data is the most powerful feature of ICN proposals. As Internet users are more interested in information rather than its location. To fulfill this, ICN proposals are designed to provide named data independent of its server name. Moreover, TCP/IP is a host centric network model that was basically designed to share expensive resources. Instead today’s Internet usage is not only limited to share network resources but for information dissemination with fast delivery rate to billions of devices and these are the major requirements that Internet should support. In addition, TCP/IP natively does not respond to any query unless an address is installed. ICN resolves these above mentioned issues by just naming the data. In ICN, naming the data is performed just above network layer [35], [103].

Naming the data makes, in-network caching easy and efficient as named data is easy to manage and search. Therefore naming reduces information retrieval delay. In addition, access strategies works efficiently if these know what (named) data is being transmitted to which node. Moreover, multi-cast forwarding outperforms because of aggregation of name base requests [36], [109].

Naming defines the structures of how to name a data. Currently two naming schemes are there that ICN models support: hierarchical and flat. Names can be human readable or not, but they are assumed to be location independent [35].

Naming (the data) supports IoT applications as IoT users are interested in information. For instance when we query about traffic condition at a specific road. Any vehicle (node) who has data, can response to our query.

2) Receiver Driven Communication: This is unique and a very beneficial feature of ICN that communication initiates only when a consumer needs. This feature makes ICN different from the current network architecture in the way that it is completely receiver driven. Further it is the responsibility of network to search for the requested data. To enquire a data, receiver places a request excluding its location or server name. Then network finds the best possible source for the requested information.

Two approaches are there in ICN, through which receiver can receive information named: coupled and decoupled approach. In coupled approach, name resolution and routing are aggregated and data is routed by following reverse path towards consumer. In decoupled approach where name resolution and routing are performed independently, any path other than, that request message follows from consumer (requesting node) to information provider, is utilized to forward response towards consumer.

As IoT devices and networks are resource constraint, receiver driven communication helps to save the network resources in the way that it can reduce number of transmissions. This is because, data will be only transferred when IoT user subscribes to an IoT device. For example, in case of smart campus, students get information about class timings from smart notice board. Administration authorities update time table on a central platform (smart notice board). Students who have subscribed to notice board can get time table updates. Moreover mobile nodes when change location, can subscribe to new nearest routers. Due to receiver driven communication, these devices can resume their ongoing transmissions.

Although sender driven communication is inherently not supported by ICN. Thus besides the advantages of receiver-driven communication, sender driven communication can be provided through the methods presented in [108]. Mostly sender driven communication is required only when some incident occurs. Therefore, this required type of communication can be provided through beacon messages [108].

3) In-network Caching: To reduce workload on the nodes, ICN supports in-network caching. In network caching helps in case of flash crowds when large number of nodes request for same data at the same instant. In situations like flash crowds, ICN caching outperforms the current network. When a request is fulfilled by any router, its corresponding data is cached on all intermediate nodes. Intermediate nodes can now response to that query while acting as server. Two types of in-network caching mechanisms are there:

1. On-path: caching is done on the path taken by request message.
2. Off-path: caching is performed out of the path.

In coupled approach, off path caching is supported by routing system. While in decoupled ICN architecture, name resolution system is responsible to provide off path caching. Caching always provide fast information delivery.

Moreover, caching enabled ICN based IoTs applications improves network performance in terms of fast delivery and reduces traffic. Incoming requests could be respond through cached data in case of network failure and node unavailability.
Figure 3. ICN Operation: Consumer requests for a specific content by nearest Routers (1,2,3,4) and Producer replies and Intermediate nodes caches that content and fulfills further request through cached contents rather than sending request towards the original Producer (IoT constraint-oriented nodes runs out of battery frequently) [35].

4) Mobility: Now wireless mobile devices are more in number than static devices, that do not change their location. Our daily life gadgets like mobile phones, tablets and automated cars are wireless and mobile. Basically host-centric communication model TCP/IP is not meant to support mobile devices. Mobile devices need to change their IP addresses. Solutions like mobile-IP patch over TCP/IP increases complexity to deal with mobile devices and presents ‘three tunnel communication’ problem [35].

In ICN mobility is efficiently provided by employing publish subscribe model. Any mobile node subscribes the network for the information it needs. Further publisher advertises the availability of information to the network. Other nodes present in the network that match the subscriptions with the publications helps to direct communication between publisher and subscriber. Moreover, it is possible that either publishers are unaware of their subscribers or subscribers do not keep record of their publishers.

A mobile device subscribes to the network and receives data. When mobile device’s handoff occurs, network shifts device connectivity to a cached node rather than the original producer. Although producer mobility is not addressed yet as it is more complex. But through in-network caching, information may be provided through cached data on intermediate nodes in the situation when information provider changes its location. These all features of ICN makes it best communication model for mobile (consumer) devices.

Therefore efficient ICN mobility support can play an important part for IoT applications like smart transport and smart vehicles.

5) Security: As Internet was designed to connect computers and forward any data over the network. This feature allowed hackers, spammer and attackers with bad intentions to transmit their own information while jamming the network traffic for rest of the users causing DoS. There were many solutions proposed and used to cater this security and privacy issues like IPSec. protocol. But they do not perform efficiently in scanning network deeply to find such malicious activities and to stop these activities. Major issue arises from application layer and network layer separation and disconnection that provide opaque packets difficult to inspect. On the other hand DPI (Deep Packet Inspection) is expensive solution to inspect individual packets. Thus TCP/IP secures terminals but not data.

On the other hand, in ICN, data packets are transparent and easy to check whether these packets are valid or from some spammer. Thus ICN data naming lessens DoS attacks and vague transmissions. Moreover no data can be transmitted unless a receiver requests for it. Inspection of named request message makes it easy to identify that response being transmitted is valid or not. ICN flat names may not human readable and short but provide self-certification. While ICN hierarchical
names are human readable, long. Therefore long names need a trust manager to verify whether data being transmitted is according to interest message or not [35].

IoT applications like smart home and e-health require high security of transmitted data. To provide this security in better way, ICN self-certified names can play a vital role. Details of ICN operation is shown in Fig. 3.

C. IoT Requirements Mapping to ICN Characteristics

IoT applications that require scalability in terms to support billions of IoT devices and huge quantity of contents can be build using ICN characteristics like naming the contents, in-network caching and content-based security. Further ICN naming and name resolution can be efficiently used to provide billion of addresses and names to IoT devices and contents respectively. To support IoT applications involving mobile devices, ICN receiver-driven communication feature along with flexible naming the contents and location independence can play an important role to make hand-off easy for mobile devices. Moreover, ICN in decoupled mode can perform easy re-registration after a hand-off of a mobile device with nearest new router. Security and privacy in IoTs can be provided through following features of ICN, for example ICN named contents make it easy to inspect that data is flowing according to query, content location independence hides the source of content, receiver-driven communication style confirms that content is arrived because receiver has requested for this content and self-certified contents ensures that the contents are same as sent by source. Heterogeneity among IoT devices can be handled easily when devices are named through ICN naming. Different types of IoT devices can operate with each other more efficiently when ICN strategy layer will be induced in IoT devices. ICN in-network caching can enable IoT networks to cache fetched data in (all intermediate) node(s) to enhance data availability in IoT network. Moreover, in-network caching decreases the frequency of fetching data from producer and thus saving network life and making it more energy efficient. Table V summarizes the mapping of IoT requirements to supporting ICN features.

D. Caching and Naming Feasibility of ICN Models and Projects for IoTs

This section presents nine famous ICN architectures such as DONA [110], NDN, COMET, PURSUIT, SAIL, CONVERGENCE, MobilityFirst, C-DAX [31] and Green ICN [32]. ICN major projects and architectures along with funding sources are presented in Fig. 4 and are briefly discussed here. Further details can be found in [35]. However, their feasibility w.r.t naming and caching techniques is discussed in Table V.

1) DONA (Data Oriented Network Architecture): The DONA [110] is first clean-slate network architecture in which information is named using flat naming technique and these names are self-certifying. DONA names consist of two parts: principal and label part. Principal part is derived from cryptographic hash of the owner (of information) and label part is cryptographic hash of the object itself. In DONA, the routers that perform data routing, name resolution and enable cache functions are known as resolution handlers (RH) or dissemination handlers (DH). Three types of messages are there in DONA i) Find message, it is transmitted from subscriber towards publisher through local RHs. ii) Register message, whenever a publisher has some information to advertise it sends register message from publisher to its local RH as well as RH of peer AS. iii) Data message, publisher replies the request by reverse following the label sequence saved in request message.

Coupled DONA makes information availability through on-path caching by caching information at RHs. While in decoupled DONA, RH provides additional registrations to provide cached data to enable off-path caching.

2) NDN (Named Data Networking): The NDN [25] is an active project from USA formerly called CCN (Content Centric Networking) [111] architecture that was a project from PARC. NDN is refining and maintaining CCN for Future Internet foundation. NDN names are hierarchical that consist of prefix from publisher. These names may or may not be human readable. In contrast to DONA, NDN supports dynamic naming as subscriber places a request a publisher generates it by assigning a new requested name. To receive a data via NDN architecture, a consumer sends an Interest message toward producer through content router (CR). Every CR maintains three data structures: i) Pending Interest Table (PIT), ii) Forwarding Information Base (FIB) and iii) Content Store (CS). PIT stores the interests that are not satisfied, FIB keeps track of named data and their corresponding data sources to forward interest and CS caches the sent data along with its name to serve in future. If upcoming interest message data is already cached in CS, CR replies it through the incoming face and removes interest message otherwise it checks it in FIB. If it exists in FIB, it places incoming face in PIT. If exactly same interest request is found in PIT, face number is placed in PIT ahead of the interest and discards interest message. When a CR receives data in at incoming face, it firstly stores in its local CS and then grabs entries from PIT and start forwarding via multicast forwarding. NDN support only coupled approach in which it integrates routing and name resolution functionalities. A CR may have more interfaces to support multiple information sources.

NDN offers on-path caching via saving data in CR’s CSs. To support off-path caching, strategy layer sends interest message towards other information sources, thus making it transparent to NDN.

NDN provides easy network administration, guard network against DoS attacks and spanning trees. Therefore, NDN is being employed in IoT applications like VANETs [112], smart home [36] and building management system [113-114].

3) COMET (Content Mediator architecture for content aware networks): The COMET [28] is designed to provide easy access of contents and fast dissemination of contents through content-aware networks. It provides names by content resolution system (CRS). Major part of COMET is that content mediation plane (CMP) mediates between network and information providers. CMP has two versions: one is based on ICN to support Future Internet through coupled approach and the other one is based on current network architecture via
Table IV

| Sr# | IoT Requirement(s)                     | ICN Supporting Features                                      |
|-----|----------------------------------------|--------------------------------------------------------------|
| 1.  | Scalability                            | Naming, In-Network Caching, Content-based Security            |
| 2.  | Naming and Addressing                  | Naming and Name Resolution (Coupled and Decoupled mode)      |
| 3.  | Mobility                               | Decoupled Mode, Naming, Receiver Driven, Location Independence|
| 4.  | Security and Privacy                   | Naming, Location Independence, Receiver Driven, Content-based Security |
| 5.  | Heterogeneity and Interoperability     | Naming and Name Resolution (Coupled and Decoupled mode), Strategy Layer |
| 6.  | Data Availability                      | In-Network Caching                                           |
| 7.  | Energy Efficiency                      | In-Network Caching, Naming                                   |

Figure 4. ICN Projects, Funding Sources and Architectures

decoupled approach. COMET accounts location of both data and network providers to work in content aware fashion.

In coupled COMET, specific naming format is not defined yet. However, whenever a publisher needs to publish any information, it can send a register message to its nearby CRS to advertise the availability of data. CRS assigns a name to this data and propagates information name along with its source name towards its parent CRS. It does not forward towards peer CRS hence saving bandwidth and support publisher to place constraint on its published data availability. Moreover when a subscriber needs any data, it places query forwarding a consume message towards its local CRS that propagates up in the network until it finds the corresponding path to publisher. When consumer message reaches publisher, it replies through content aware routers (CaRs). Each CRS maintains its own CaR to trace back subscribers. Then publisher replies to its corresponding CaR that routes data message towards subscriber. In COMET name resolution is the responsibility of CRS while data routing is performed by CaR.

COMET support both on-path and off-path caching. On-path caching employs probabilistic caching technique and centrality scheme. Off-path caching is achieved through information registration with CRs as well.

However, COMET is less suitable for specific IoT applications but more suitable in data dissemination due to probabilistic caching.

4) PURSUIT (Publish Subscribe Internet Technology): PSIRP [115], latterly known as PURSUIT [26] project consists of three different components that work together to enable name base networking: i) Rendezvous Function (RF), it finds advertisement against requested subscription and is performed by rendezvous node (RN). RNs work together to build Rendezvous NEtwork (RENE) ii) Topology management function (TMF), it looks for a suitable path from publisher to subscriber through topology management node (TN) iii) Forwarding Function (FF), it actually forwards data from
Table V

| Project Name, Duration and Funding Source | ICN Architecture Name | Naming and Caching | Extent of Suitability for IoT Applications |
|------------------------------------------|-----------------------|--------------------|-------------------------------------------|
| DONA 2007 UC Berkeley                    | DONA                  | 1. Uses flat self-certifying names, that cannot provide scalability. 2. DONA offers both on-path and off-path caching | Not suitable as flat names cannot manage IoT billions of devices data contents |
| CCN (2010-2013) by PARC, NDN by NSF and UCLA | NDN                  | 1. Provide hierarchical, static and dynamic named data through easy administration. 2. NDN offers both on-path and off-path caching (cache everything) | Highly suitable as IoT devices are constraint oriented, and needs scalable naming technique |
| COMET (2010-2012) EU Framework 7 Programme | CURLING              | Unspecified naming scheme, enhance easy access and fast data dissemination through content aware networks, especially supports flash crowds. 2. Works on both on-path and off path through prob-caching) | Not suitable for IoT as naming scheme is not defined but suitable for data dissemination applications |
| PSIRP and PURSUIT (Sep 2010-Feb 2013) EU Framework 7 Programme | PURSUIT            | 1. Flat naming provides a decoupled architecture that separates name resolution and data forwarding. 2. Provides effective off-path caching | Not suitable as flat naming scheme cannot manage billions of IoT devices and data contents but suitable for data dissemination applications |
| 4WARD (2008-2010) and SAIL (2010-2013) EU Framework 7 Programme | NetInf              | 1. Flat self certifying or hashed naming divides the whole operation in two-steps: name resolution by NRS and data routing by node itself. 2. It offers both on-path and off-path caching | Not suitable as flat naming scheme cannot manage billions of IoT devices and data contents but suitable for data dissemination applications |
| CONVERGENCE (2010-2013) EU Framework 7 Programme | CONET               | 1. Both (hierarchical and flat Naming) schemes, converges to NDN and DONA in some aspects, designed for multimedia contents, partially dependent on IP based architecture and partially on ICN based. 2. Both on-path and off-path caching is provided | Not suitable as IoT application requires more than the management of only multimedia contents. IoTs architecture also needs to manage simple contents. But it is suitable for data dissemination applications. |
| MobilityFirst FIA (2010-2014) and FIA-NP (2014-to date) NSF, USA | MobilityFirst MF      | 1. MF uses flat, self-certifying naming scheme, 160-bit long names to avoid collision and make comparison easy and fast. MF provides best mobility services and employs IP based architecture in an efficient way 2. MF offers on-path caching | Highly required by IoT as it can have both mobile and static devices |
| C-DAX FP7-ICT (2012-2016)                | C-DAX                | 1. Information is managed in the form of topics using flat and attributes-based naming | For cyber-secure smart-grids and electric vehicles. |
| Green ICN (2013-2016) EU Framework 7 Programme | Green ICN G-ICN      | 1. Contents can be named by using both flat, self-certifying and hierarchical naming schemes with attributes and arranged in topics 2. User assisted caching is employed | Highly required by IoT disaster management and multimedia contents dissemination applications |

publisher to subscriber on the path provided by TMF. In PURSUIT, information objects must belong to at least one group. Each group is assigned an identity, Scope ID (SID). Information object itself has its own identity, rendezvous ID (RID). Thus in PURSUIT, names are flat consisting of a pair of multiple SIDs plus single RID. PURSUIT operates in a decoupled fashion as routing and name resolution is done by separate modules. When publisher has data to make it available for the network; it sends a publish message to its nearby RN. It forwards this message towards corresponding scope RN through DHTs. Whenever a subscriber needs data it forwards a subscriber message to its local RN. This RN then forwards this subscribe message towards same RN by crossing global RENE through DHTs. RN direct TMN to calculate the path from subscriber to publisher. TMN sends this calculated path towards publisher in start publish message. Publisher places Data message to nearby forwarding node (FN) and it finally reaches subscriber by crossing multiple FNs.

Pursuit offers caching in both on-path and off-path modes. On-path caching on FNs does not make any sense as if same subscriber needs data again, it will contact nearby RENE, which in turn, repeats all the process again. Thus off-path caching works in PURSUIT to enable caches as publishers.

Like COMET, PURSUIT is also less suitable to any specific IoT application rather it can be used for data dissemination.

5) SAIL (Scalable and Adaptive Internet solutions): Both projects SAIL [116] and 4WARD [117] have shaped an ICN based architecture named network of information (NetInf) [27]. SAIL architecture combines the naming techniques of NDN and PURSUIT. Flat names are used to find a matching publication for required data like PURSUIT. A flat name consists of a pair of authority and local. These two parts can be either hash or self-certifying components. If publication matches then long hierarchical names are used by routers to locate publisher like NDN. SAIL can operate in both decoupled and coupled fashion. To operate in decoupled fashion, name resolution system (NRS) translates names in addresses like IP address. To advertise any information, a publisher sends a publish message along with its address, this address is saved in locator part L for mapping. Local NRS aggregates all locators L with the same authority part A through a bloom filter and sends to global NRS. Any subscriber interested in that data sends GET message to its local NRS which contacts global NRS. Global NRS sends its reference towards local NRS which sends it to subscriber. Subscriber uses this address and sends GET message towards publisher. Publisher replies with DATA message to subscriber on the same reverse path. This is decoupled approach in the way that name resolution involves local and global NRS while for data routing subscriber sends...
message towards publisher. To enable coupled mode a routing protocol is used to advertise the routing tables of content routers (CR). When any subscriber is interested in any data it sends a GET message for it then CR sends a message towards publisher. As data is found then it is forwarded using the reverse path. In hybrid mode, NRS helps by providing GET message some hints about publisher location. GET message uses these hints by forwarding itself in multiple directions. Therefore, SAIL architecture can operate in coupled, decoupled and hybrid mode.

SAIL provides on path caching by caching data on the intermediate nodes as well as by storing data on CRs. SAIL may employ caching mechanisms to deal popular contents near the subscriber or may employ the large caches and small caches to reduce the traffic towards global NRS and publisher.

Like COMET and PURSUIT, SAIL also employed for fast data dissemination rather than any specific IoT application.

6) CONVERGENCE: The CONVERGENCE [29] project partially depends on existing IP based architecture. CONVERGENCE has targeted mainly multimedia contents. A versatile digital item (VDI) based on MPEG-21, is defined as a common container for each digital multimedia content. Publishers advertise VDIs and subscriber can subscribe by requesting these through a network known as content network (CONET). To be accessed via IP network, CONVERGENCE message headers also contain IP message headers. This IP message header is used by CONVERGENCE based router to treat IP datagrams according to IP architecture. In CONVERGENCE content names can be either flat like DONA or hierarchical like NDN. Basic name format consists of name-space ID and name of information. As CONVERGENCE converges to NDN, so hierarchical naming is used frequently. It has many similarities with NDN like a subscriber issues an INTEREST message to publisher through intermediate nodes (IN) or border nodes (BN) and as INEREST message reaches publisher it replies with DATA message on the reverse path. It differs with NDN, as BN do not support fully name based routing and whenever any BN does not find path towards publisher it contacts NRS. INTEREST messages attach the BNs address they pass and BNs can apart multiple hops.

In CONVERGENCE coupled approach is employed by combining name resolution and data routing except that it may add IP nodes and may contact NRS to ask for appropriate path to reach Publisher. As a result of this coupled approach, it only provides on-path caching.

Therefore, CONVERGENCE combines the features of NDN with its own features to use IP based architecture. It is an overlay approach rather than purely ICN based. In CONVERGENCE each individual packet is scanned only at the subscriber. For this reason, it may make DoS (major security concern of current architecture) possible.

The CONVERGENCE project, like SAIL, PURSUITS and COMET, is also less suitable for IoT applications and can be employed for general information dissemination and for easy management of multimedia contents.

7) MF (MobilityFirst): The MF project [30] was carried out in 2010-2014 with the aim to provide a clean-slate architecture for mobile devices. Under MF project (funded under FIA), it is aimed to design and evaluate mobile data, IoT use cases and mobile entities. FIA-Next Phase (FIA-NP) also plans to unify Future Internet while employing advanced cellular networks like 4G and 5G.

Main features of MF include i) separation of naming and addressing, implemented via a fast global dynamic name resolution service, ii) self-certifying public key network addresses to support strong authentication and security iii) generalized delay-tolerant routing with in-network storage for packets in transit (iv) flat-label inter-network routing with public key addresses v) hop-by-hop transport protocols operating over path segments rather than an end-end path vi) a separate network management plane that provides enhanced visibility vii) optional privacy features for user and location data and viii) an integrated computing and storage layer at routers to support programmability and evolution of enhanced network services.

In MF names are assigned and translated via global naming resolution service (GNRS). Whenever a device has data it contacts GNRS to get a name for it. This flat name is 160-bit long and known as globally unique identifier (GUID). Every network device must has its own GUID and GUIDs of the all services it produces. By naming network devices both host-based and name-based communication is possible. When publisher has data to advertise it first consults GNRS to get GUID for the data and to register this GUID with GNRS. When subscriber needs data it places a GET message with GUID of requested data on its local CR. Local CR contacts GNRS by providing GUID of the requested data to find the full path/ partial path/ next node. CR then forwards the GET message towards the path of IP addresses that GNRS provides. Publisher replies with DATA message towards subscriber by getting the address attached in GET message. This is the beauty of MF that supports mobility efficiently. For less dynamic operations, MF employs network addresses based resolution or GNRS resolution once. For more dynamic operations, GNRS consultancy may be required multiple times. Thus if GUID needs to be located from GNRS, information retrieval may presents some delay.

MF offers on-path opportunistic caching to response subsequent requests. To support off-path caching, new sources need to inform and register themselves from GNRS. As CR can consult GNRS as often as it needs. Moreover some constraints can be implemented on CR to deal how many times CR should consult GNRS. Host (both publisher and subscriber) mobility is handled by GNRS. GNRS updates all references and can be accessed via accessing GNRS. Contents are flat that can be self-certifying.

MF is designed to support mobile devices and is employed in IoT applications like mobile networks, cellular networks and bus management systems [113].

8) C-DAX (Cyber-secure Data And Control Cloud for Power Grids): As obvious from its name, ICN based architecture under the C-DAX project is specifically designed for smart grids. ICN based cyber secure communication middleware is designed for smart grids. Information is named and arranged in the form of topics. C-DAX works in decoupled mode to make transparent communication possible.
also work with smart grid protocols. By employing ICN concepts, it provides cyber secure, resilient and inter-domain communication with three modes: streaming, query and point-to-point. Moreover C-DAX employs on-path caching.

C-DAX works for IoT smart grid application and electric vehicles.

9) **G-ICN (Green ICN):** The G-ICN aims to provide ICN based energy efficient communication solutions for disaster management (situations like flood and earthquake) and video delivery. G-ICN employs ICN (specifically NDN) features like decoupled communication and in-network caching to enable services for disaster management. Fast data dissemination of multimedia contents, is enabled through the use of in-network caching and by naming the contents. Both naming schemes e.g., flat self-certifying and long hierarchical, are employed to manage information in the form of topics. Moreover, fast and easy delivery is made possible by practicing naming and in-network user assisted caching.

The G-ICN is definitely necessary for IoT applications like efficient delivery of multimedia contents in VANETs and in disaster management as reliable communication solution.

These nine ICN projects, architectures and their corresponding feasibility for IoTs is summarized in Table [VI]

**IV. ICN RESEARCH FOR IOTs**

As discussed in above sections, ICN offers many exciting features like name base routing, better mobility, secure receiver driven communication, effective and energy saving in-network caching. Therefore ICN is becoming the ideal candidate to make the future Internet better performance wise. As ICN can fulfill future internet requirements like fast and easy information dissemination and flash crowds. And for IoTs, ICN can serve efficiently to build many applications like smart transport, smart home, smart health and smart grid.

To meet IoT environment needs, ICN research community is trying hard to build efficient architecture for IoTs. In this context, few attempts are made to provide ICN based IoT architecture. In following the text, we present these ICN based IoT research efforts and some important contributions are summarized in Table [VI].

ICN is the ideal candidate for IoT, it is argued in [37]-[119]. The need for naming schemes, name resolution mechanisms, mobility, information look up service, contextual information retrieval, trust models, energy management, device management and monitoring, access policies when data is distributed in multiple caches and information forwarding in a delay tolerant manner is highlighted by keeping the IoTs constraints in mind. Talking about ICN for IoTs that either it will work as clean-slate or as an overlay, authors in [37] argue that ICN should not replace the current architecture for IoT; rather it should work as an overlay architecture.

While to support clean-slate architecture of ICN for IoTs, NDN based high level node architecture is proposed in [23]. Three layers NDN-IoT architecture, consisting of application layer, NDN layer and thing layer, is presented. Node architecture includes content chunks instead of IP address enabling name based networking. Strategy layer is introduced to provide transport and forwarding tasks according to access technologies and application needs. NDN operates at the network layer and performs its duty with two planes namely control and management plane and data plane. Control and management plane perform the task like routing, configuration and service models while data plane handles interest and data messages and related jobs like strategy caching. However they only considered limited static devices and did not provide any implementation details.

As natively NDN supports pull based communication. In [118], three different strategy schemes are presented to provide push-type communication. First scheme *Interest notification*, modifies interest message by including small data need to be transmitted. This small data is not meant to be cached. Second scheme *Unsolicited data*, transmits small packet of uData that is not feasible for routing. In third scheme *virtual interest polling (VIP)*, receiver transmits long live Interests such that whenever data is available, producer replies and on the failure consumer can re-transmit Interest again. They presented the analytical model for Interest notification, Unsolicited data and VIP and implemented the model in MatLab. VIP outperformed in terms of network resources used and is suitable for massive IoT environment while other two techniques are suitable for situations where battery is critical source.

Moreover to address and target IoT both static and mobile devices, an unified ICN based IoT platform is discussed in [113]. NDN and MF are selected to cater both static and mobile devices. They provided comparison between/among both NDN and MF through building management and bus management system scenarios. Different sensors and actuator are considered as static devices while buses are considered as mobile devices. They argue and found that MF outperforms NDN when mobile objects like buses are involved while NDN outperforms MF only when static devices are involved. They have implemented NDN and MF in NS3.

To retrieve data from multiple producers against any single interest message, NDN based framework is presented in [109]. They provided solution to cater multiple sources data retrieval through data compression of packets like interest and data message, addition of Exclude field in Interest packet and consumer aided collision avoidance scheme. This multi-source framework saves bandwidth, maximizes data diversity and reduces collection time.

CCN is identified as the best candidate for IoT rather than RPL/UDP (in IPv6 based 6LowPANs) through simulations in RIOT OS[106]. Wild deployment of ICN is carried though 60 nodes located in several rooms of several buildings. CCN lightweight version, CCN-lite is simulated and they enhanced CCN through two proposed routing flavors (vanilla interest flooding (VIF) and reactive optimistic name-based routing (RONR)). Both VIF and RONR are evaluated to show that these protocols reduce routing overhead for constraint oriented devices. They also addressed positive impact of caching and naming the data. In addition they also highlight the need for smart caching and small naming in ICN based IoT. Further NDN based architecture (in Python language and Javascripting based browser to visualize the data) is explored to secure a building and it is installed in UCLA (University of California
Table VI
ICN-IoT LITERATURE

| Ref#  | Summary                                           | Architecture | Simulation/Tool |
|-------|--------------------------------------------------|--------------|----------------|
| [123] | High level node architecture                     | NDN          | –              |
| [119] | Push-support is discussed                        | NDN          | MatLab         |
| [113] | MF-IoT and NDN-IoT based models discussed separately | NDN and MF   | NS3            |
| [119] | Highlight the need for naming and caching        | ICN          | –              |
| [109] | Multi-cast for IoT                               | NDN          | ndnSim         |
| [106] | Wind deployment of IoT nodes through NDN         | NDN          | RIOT           |
| [120] | Access control, trust establishment and secure proxies for IoT security | PURSUIT | Not mentioned |
| [121] | Access control, encryption based access control and browser based data visualization of data captured through sensors to secure a building | NDN | Python-based data publishing service and browser-based data visualization using Javascript prototype |

at Los Angeles [121]. Name-based and encryption-based access control method is proposed and implemented to secure sensitive data. This is a initial prototype to showcase the scalability performance achieved by NDN instead of IP based security systems. Moreover in [120] security methods are presented on the basis of PURSUIT ICN architecture to secure IoT constraint-oriented static devices. They provide mechanisms for secure access control, secure information proxies and trust establishment.

In [123] a forwarding mechanism is presented for vehicles by incorporating one immediate vehicle resources. Forwarding mechanism ranks the vehicle based upon multiple factors and selects one as a forwarder among present vehicles. While [121] provide a scheme dynamic PIT entry lifetime (DPEL) to reduce number of PIT entries. Hence it minimizes the usage of battery of mobile nodes and makes routing and forwarding easy and fast. The need for source mobility is highlighted while discussing existing solutions in [124].

Therefore, we can state through the above mentioned research efforts that it is obvious that ICN can play a vital role in building the network architecture for the highly challenging research environment of IoT. Although the purpose of mentioning these efforts here, is not to compare these in any perspective but to showcase the efficient applicability of ICN for IoT along with fertility of this research era. Moreover, we are confident that exploring ICN for IoTs is a fertile research era with multiple unresolved issues identified and discussed with suggestions in Section VIII.

V. ICN-IoT CACHING SCHEMES

Inherently, the current Internet is designed to forward all requests of same content towards original producer and hence increases network load, retrieval delay and bandwidth consumption. The current Internet lacks support for data dissemination and fast retrieval of the content. These issues raised the need of in-network caching. To cope these shortcomings of the current Internet architecture, Content Delivery Networks (CDNs) were introduced. By employing CDNs, caching is deployed as an overlay patch at application layer (web-caching) of the current Internet architecture. CDNs are costly to implement and do not utilize network resources efficiently in case of dynamic flash crowds. Thus, in the design of the future Internet architecture caching is added as an important feature. In ICN based future Internet architectures, caching is implemented at network layer that directly operates on named information. ICN architectures DONA, NDN, SAIL and MobilityFirst primarily support on-path caching while PURSUIT, COMET and CONVERGENCE support both on-path and off-path caching [35].

In ICN based IoT, caching is highly required to disseminate information quickly towards edge devices in a cost-efficient way. As some IoT applications need fresh contents with some specific timing requirements. And mostly, IoT contents are ephemeral in nature that need to replace with the newer versions, for instance, temperature value of a room needs to be monitored and updated continuously. Moreover, as IoT nodes are highly heterogeneous that may differ in the processing resources (i.e., constraint-oriented and powerful nodes) and IoT networks are mixture of wired and wireless technologies.

In IoTs, caching at intermediate devices or routers offers many benefits. As receiver is dissociated from original producer, therefore by caching the contents, security improves and scalability of IoTs network increases [23]. Energy efficiency of constraint oriented devices can be improved and mobility can be handled in more better ways [48]. Resiliency and life of IoT networks can be improved by employing caching carefully [125].

As caching offer many advantages, it also puts same restrictions and complications on the design of caching strategies for environment like IoTs. To design ICN based caching for IoTs, caching strategies must count for some properties of content to cache and node that intends to cache it. Content properties can include popularity, freshness, ephemerality, timing and specific producer while caching node properties can count for battery (power level), distance of node from producer (or/and consumer) and remaining memory. On the basis of this mentioned observation, we provide caching placement strategies into following three categories:

1) Content Based Caching (CBC), these strategies decide what content to store on the basis of content properties.
2) Content and Node Based Caching (CNBC), these
schemes decide whether a node should cache content or not, depending on both content properties and node resources (like battery life).

3) Alternative Caching Schemes, algorithms that include distance of a node from producer or position/role in network in caching decision lies in this category. ICN based caching node architecture and cache coherency are also discussed in this sub-section.

An overview of ICN-based caching schemes for IoTs is presented and summarized in Table VII. A caching strategy is further divided into following three phases:

1) Content placement into cache, in this phase cache space is allocated to contents on the basis of content and/or node. Content placement schemes include cache each and everything (universal caching), probabilistic caching etc.

2) Content replacement from cache, in this second phase, when cache becomes full with contents and there is no space vacant for next upcoming content, it is decided to which already existing content it will replace. Content replacement schemes include LRU (Least Recently Used), LFU (Least Frequently Used) etc.

3) Cache coherency of contents in cache, in this phase, validity of contents residing in cache is checked.

Further, caching performance measures include retrieval delay, hit ratio, network lifetime (how long network will exist in terms of connectivity), interest re-transmissions (total number of interest sent to get a content) and energy consumption per content (how much energy is required to decide about cache a content and/or replace it).

ICN based caching placement methods have been extensively investigated in the context of IoTs in [126], [127], [128], [129], [130] as depicted in Fig. 5. In the following subsections, we survey caching placement schemes along with caching replacement schemes. According to Fig. 5 we sub-classify caching placement schemes into three categories: Content Based Caching (CBC), Content and Node Based Caching (CNBC) and alternative caching schemes.

We further classify CBC on the basis of freshness, probability and CNBC schemes according to freshness, popularity along with node properties. We sub-classify alternative caching schemes into infrastructure based caching, caching node architecture and cache coherency.

A. Content Based Caching (CBC) for ICN-IoT

Most of IoT applications that process the contents put rigorous constraints on the contents. Some IoT applications demand contents with freshness constraints while other may demand the content with high probability. Probability for a content, can be set according to the popularity or in a random fashion. In this section, we present ICN based caching
strategies for IoTs, those include such content properties in caching decision.

1) Freshness of Content: IoT contents required by IoT applications are transient in nature that update their values continuously (e.g., temperature sensors update their values and consumer could request the most recent value or of specific date or time). Updated information can be received through specifying freshness value. Thus, caching strategies dealing with freshness are highly important for ICN based IoTs. In the following subsections, we present attempts that consider freshness in ICN based caching design for IoTs.

a) Specific freshness Caching: In [126], freshness based caching scheme is proposed to facilitate consumer applications inquiring contents with specific freshness values. Consumer has to specify the freshness requirement of the value it needs. Intermediate routers or producer can set (or even can change) the freshness value for the required content raising DoS attack. In CS, a new field to set freshness and a check to compare the time stamp of cached data with the requested by consumer have been added to the existing CCN. Consumer is assumed to send request for same content and with specific freshness values. Interest packet has been modified by adding a new field freshness parameter. Producer nodes are Wi-Fi nodes connected to Access Points (AP). LRU has been applied as cache replacement strategy. Freshness value added more control of the consumer in the quality of data being fetched. By adding, ratio of active time of restrictive in freshness consumer to active time of less restrictive in freshness consumer, caching performed better for IoT applications that need recent data. However in [127] only caching scheme has been presented.

b) Caching with same freshness: In [127], IoT environment needs and corresponding ICN features have been discussed. Bandwidth and energy consumption have been measured for CCN based IoT scenarios with varying number of nodes (both consumers and producers) and compared against IP. CCN data packets have been modified by including both freshness of content and fraction of size of CS. NS3 and ndnSIM have been used for IP and CCN respectively. Application for consumer has been implemented in the way that it requests for same data from different producers. Total one hundred nodes have been included in the simulation while half of these nodes were producers and half were consumers. IP based producers were WiFi mobile nodes connected to AP, while ICN consumer nodes were set to inquire data of same freshness value. LRU has been applied as cache replacement scheme and cache placement scheme has been designed to include freshness and variable CS size fraction. Impact of increasing sensors require more bandwidth rather than increasing number of consumers. This is good for IoT scenario where number of consumers are uncontrollable (e.g., hotspot or flash-crowd). They have found that IP based case consumed more bandwidth than CCN. Impact of freshness has
reduced performance assumed to achieve through caching. To enforce caching, small CS would be enough if freshness is highly required. However, considered IoT scenario has fixed number of nodes and implementation has not been performed for dynamic IoT scenario.

2) Probability of content: Some IoT applications that require mix contents from multiple or single producer(s) like in smart traffic, a car owner may be interested in the traffic condition ahead, temperature of that area, exact location of the vehicle and map towards its destination. Therefore, ICN based caching strategies for IoTs should include factors to cope these applications requirements. In this context, random probability assignment can provide diversity in cached contents.

a) Always and Probabilistic Caching: In [128] authors have implemented NDN for IoTs and applied Always and Probabilistic (with P=0.5) caching schemes. LRU and Random replacement algorithms have been applied as cache replacement schemes. Simulations were performed in ndnSIM and NS-3. Total of 36 nodes were included in simulation, out of which, four were destined as consumers and six were randomly selected as producers in a 400m X 400m area. Probabilistic caching scheme and LRU cache replacement scheme, in a combination, achieved higher results for cache hit ratio, retrieval delay and interest re-transmissions. Cache size has been varied from 1-4KB but optimal results were achieved when CS size was 4KB. Probabilistic caching and LRU replacement scheme ensured content diversity and most recent contents in the IoT network, that are important requirements of IoTs. Though, authors have found caching (even with small CS) beneficial for IoTs.

In [106] impact of Always caching (Where P is always 1), is evaluated on RIOT OS [133] for a large building. They argue through their results that caching is highly beneficial for devices having small memory. Authors support in-network caching for IoTs because it saves bandwidth and energy consumption.

B. Content and Node Based Caching (CNBC) for ICN-IoT

In this sub-section, we survey ICN based caching schemes that include both content and node parameters. Content properties like freshness, popularity and node important parameters like battery level, cache size, node location and role in the network are considered for constraint-oriented IoT devices.

a) Probability of Freshness and Node Properties Based Caching: In [130], authors presented probabilistic Caching STRategy for the Internet of thinGos (pCASTING), a caching mechanism considering content property (freshness) and node properties (battery level and cache occupancy). For caching replacement, LRU has been implemented. pCASTING has been compared against cache each and everything (CEE), probabilistic caching (P=0.5) and without caching. Simulations were performed in ndnSIM and NS-3. Total 60 mobile nodes were included in the scenario. There was only one producer and eight consumers were selected. pCASTING achieved higher cache hit ratio and received data packets by consumer. Retrieval delays were less than probabilistic and no caching but higher than CEE. However, only one producer has been assumed to reply. Popularity of content was not present in the cache decision.

b) Popularity and Node Properties Based Caching: In [131] a caching scheme has been proposed using data freshness, request rate and router properties. Routers have been assigned the task to compute the probability of content, using content properties (freshness and request rate (popularity)) and node properties (incoming request rate and location of node in network). Numerical evaluation has been presented in Matlab. However, proposed caching scheme is for multimedia contents (40GB link has been mentioned in simulation parameters) and it requires extensive calculations, hence it is less suitable for IoT low power, constraint oriented devices to perform such complex and power-consuming calculations. Moreover, as mobile nodes change locations frequently (network topology changes), proposed method is highly suitable for static devices. As static devices do not face battery issues to perform such extensive calculations. However, they have not discussed about any caching replacement algorithm.

C. Alternative Caching Schemes for ICN-IoTs

In this section, we provide a comprehensive overview of caching schemes that do not focus on a particular method (i.e., content or node based caching) but present caching schemes for IoTs from other perspectives. We categorize these ICN based caching methods for IoTs into overlay caching and cache coherency schemes because they provide caching network architecture on the existing Internet and cache coherency mechanism for ICN-IoTs. Although ICN based caching-node-architecture presented in [125], is not specifically for IoTs, but we include it to cope with the IoTs disaster management.

1) Overlay Caching for ICN-IoTs: An overlay shared caching scheme based on ICN is presented in [129]. A content management (CM) layer is introduced in Fixed and Mobile Converged (FMC) network architecture. This CM layer can be controlled through network provider or content producer. CM layer decides where content can be cached using its cache and metadata management schemes. Unified Access Gateway (UAG) node stores and forwards the content to any requesting node in FMC network while network is responsible for transmission of content. A cache controller (CC) is integrated in UAG that provides optimal caching and pre-fetching plans. HTTP traffic passes through this overlay caching. A Config packet is added in the CCNx to carry information about caching and cache replacement scheme. Updated CCNx provides transparent overlay caching and in pre-fetching process CC sends Config packet to cache node and which in return sends Interest message to overlay cache and overlay cache respond with Data packet. To provide mobility, they used BonnMotion [134]. Better performance of system is achieved in terms of, less number of packets sent towards original server as more packets get response from overlay caching, average latency and uninterrupted playback than the current system. Presented caching strategy and management scheme offers Caching as a Service (CaaS).

2) Client-Cache and Cache Coherency for ICN-IoTs: The work in [132] presents, an ICN based cache coherence
algorithm and a client-based caching strategy for M2M. Client-cache is named to represent the fact that content is saved in node near to the client node. Authors proposed client-based on-path caching strategy with less number of nodes and by using nodes that were close to receiver. A cache coherence algorithm has been presented to check the validity of contents. Proposed cache coherence method used expiration-based coherence with variable time expiration for every content. Client-based caching strategy was compared against Leave Copy Everywhere (LCE), Leave Copy Down (LCD), Probability caching, Betweenness Centrality. Client caching along with coherence algorithm has achieved better results in terms of hop reduction ratio, server hit reduction ratio, response latency and validity percentage of contents. To the best of our knowledge, this is only one paper that investigate cache coherency for ICN based IoTs. However, cache size, that is selected, is much larger to suit for low memory devices to hold a large amount of contents. Moreover, discussion about IoT applications that require fresh content is missing in the proposed method.

3) Caching Node Architecture for Disaster Management: Authors in [125] consider the disaster situation and presented the solution to recover data through cache enabled nodes. A caching scheme is presented to collect fragmented data when network is fragmented or some device (producer) has left the current network. They have modified traditional CCN by introducing Satisfied Interest Table (SIT). An expression is presented to show until when content can be available and calculate its disappearance time. It is specifically designed when producer is moved and network got fragmented (disruptive Scenario). They tried to prolong a content availability through in network caching. Connectivity between friends and family is more crucial and bulk of data is produced in such situations. NDN router architecture is modified by augmentation of SIT. SIT will keep track of users with same interests and got required data. SIT will forward interest packet to users on the basis of entries it has saved. SIT entries are erased only when that user left the network. Interest packet is modified to be satisfied by producer or satisfied consumer by introducing Distention Flag (DF). If DF is 1 SIT will provide the satisfied user with same interest and now will provide the data against requested interest. Data Packet is same as of NDN. However, this scheme requires a lot of memory so it is natively not suitable for IoT small devices. But intrinsically suitable for nodes with excessive memory and it can be employed somewhere in IoT networks (e.g., as a backup nodes in IoT disaster management applications). It requires other users willingness to disseminate data and respond queries that can put a lot of burden on the network management and can raise security issues.

D. Summary

We have surveyed ICN based caching schemes in the context of IoTs and provided a classification in Fig. 5. We have broadly categorized ICN-IoT caching mechanism into three phases: caching placement, replacement and coherency phases. Caching schemes have further categorized into three strategies: CBC, CNBC and alternative caching. CBC schemes compute properties for every content, which include freshness and popularity of content. Researchers have put more focus on exploring the content freshness while popularity has been explored in few approaches. Therefore, ICN based content popularity caching for IoTs, seeks urgent attention from research community.

On the other hand, it is important to consider both node and content properties while making caching decision. On this side, a few efforts have been made to combine both features in cache placement strategies [130]-[131]. For this type of caching we categorize it into CNBC strategies. CNBC strategies include content properties along with IoT node characteristics like battery timings, CS size, node position and caching module designing in the node and IoT network type. As IoT nodes assumed to have low processing power, memory and battery. However, caching current literature is missing IoTs low power and low memory characteristics of nodes and IoT applications with moving devices. Moreover, caching strategies are lacking in push traffic type consideration for IoT network.

In comparison to decide about optimal caching schemes in ICN based IoTs, CNBC is better than CBC alone in terms of throughput but obviously it requires more resources to compute about caching decision. ICN based energy efficient caching schemes for IoTs are also needed to explore by research community.

Besides both CBC and CNBC, we categorize remaining ICN based caching schemes for IoTs into alternative caching schemes. This include application specific caching node architecture like disaster management application, cache coherency protocol and overlay caching. This third category is decided independent of both node and content properties.

The survey proves that CBC has been explored to some more extent than CNBC. This is because CBC protocols directly deal with content properties like freshness and popularity. As every IoT application demands contents with different properties, for example, real-time applications demand highly fresh contents while flash crowds need more popular contents. As a result, CBC schemes are easy to explore for IoTs application scenarios. On the other hand, CNBC schemes are somewhat difficult to implement as ICN based IoT node and network architecture are still under research and construction phase.

In caching replacement strategies, mostly LRU has been implemented in normal nodes due to its better results. While LFU has been considered for edge nodes. Random replacement scheme is easy and simple to implement that ensures high data diversity as well.

So far, there is only one cache coherency protocol for ICN based IoTs [132], thus ICN based coherency protocols for IoTs are urgently required to provide content validation in IoT applications.

In the nutshell, our extensive survey of ICN-IoT caching schemes indicates that ICN caching provides better IoT network performance and improves data delivery. Future research needs to explore CNBC caching schemes for IoTs constraint oriented nodes while accommodating both transient and ephemeral contents.
VI. ICN-IoT Naming Schemes

Fundamentally IP based Internet was designed to communicate between academic devices, but with time, Internet usage has expanded from academic communication to fulfill society communication needs. Later on, as well as currently, with the help of add-on and specific purpose patches, IP based Internet tried to fulfill current needs of society. As a consequence, by adding patches, IP based Internet architecture provides current needs at the cost of more complex, extra expensive, delayed communication and sharing of content. With the time and keeping current expectations from Internet in mind, researchers proposed the idea of ICN that is based on name based networking. The named content can be accessed independently irrespective of its location of existence. In ICN, the name of content requested is required instead of sender and receiver address pair. Therefore, this makes ICN as receiver-driven communication model in which receiver is responsible and have full control over whole communication instead of sender. Further, network is responsible for and will have to look for content providing best source [35]-[34].

As users are more and more interested in getting content rather than the location of the content from where it is coming, ICN approaches provides the ways to name data according to some constraints. User can get requested contents by only providing their names.

ICN naming can also outperform in naming IoTs contents. IoTs contents are transient in nature and it is undoubtedly possible for one content to have many versions based on time and sensors that generate same information. Moreover IoTs contents are huge in number like billion of billions contents are likely expected to produce in any single second and IP based Internet cannot address 50 Billion [135] connected devices efficiently. According to CISCO report, there will be 12.2 Billion IoTs smart and constraint-oriented connected devices in 2020 [136]. In addition, IoT network architecture is assumed to support scalability and heterogeneity.

Mainly there are two naming techniques (hierarchical naming structure and flat/hash naming) that are available through ICN architectures. CCN [137] / NDN [138] name contents in hierarchical manner while other ICN approaches (DONA [110], PURSUIT [115], COMET [28], MobilityFirst [30], SAIL [116] and CONVERGENCE [29] ) follow flat self-certifying names. Third naming scheme, attribute based has been used initially in CBCB (Combined Broadcast and Content Based) routing [139] and can be used in combination with prior two naming techniques [140]-[141]. However, most of the research efforts considered and explored hierarchical naming technique for IoTs [142]-[143]-[107]-[106]-[114]-[56]-[48]. Some researchers focus on hybrid naming schemes incorporating both hierarchical and flat with attribute based naming [144]-[112].

Therefore, naming IoT (devices and) contents through ICN ensure, efficient addressing and scalability, more security, better mobility and support for heterogeneous devices [47]-[48].

A. Hierarchical based ICN-IoT Naming

These names are human readable names and offer name aggregation. Hierarchical naming is used in NDN and CCN approaches. It follows the hierarchical structure to name contents like contents are named on web pages through URLs. Hierarchical naming provides good compatibility with the existing Internet applications and supports name aggregation. Through variable length, hierarchical names are highly scalable that fulfills the ultimate requirement of IoT contents and devices that are huge in number. Searching for a specific name through hierarchical naming already has good compatibility with existing web-browsers architectures. Hierarchical names reduces the routing table information through name aggregation [140]-[141].

On the other hand, long and variable length hierarchical names cause degradation in search efficiency and for low power devices it could create more performance degradation. In [145]-[107] hierarchical content naming scheme is used to provide naming of contents. This work was conducted to design, implement, and integrate a CCN communication layer in Contiki based on named data for wireless sensors and networking embedded systems. A CCN name is hierarchical name attributed to content. It simply consists of a series of components of arbitrary lengths. No limitations are imposed that what sequences of byte will be used. The implemented communication layer specifies only the name structure and does not assign any meanings to names. It is up to applications or global naming conventions to set and interpret meanings

Figure 6. ICN-IoT Naming is categorized into four categories: ICN-IoT Hierarchical Naming Schemes, ICN-IoT Flat and Self-Certifying Naming Schemes, ICN-IoT Attribute-based Naming Schemes and ICN-IoT Hybrid Naming Schemes
Table VIII
ICN based IoT Naming Schemes are summarized according to the Fig. 6. Here NLAPB is for Name Lookup solution with Adaptive Prefix Bloom Filter.

| Reference | Architecture | Comparison | Parameters Evaluated | IoT Application | Simulator (OS, Programming Platform, Language) |
|-----------|--------------|------------|----------------------|-----------------|-----------------------------------------------|
|           |              |            |                      |                 |                                               |
| Hierarchical Naming Schemes for ICN-IoT |
| [145]-[107] | CCNx         | IP         | 1. Retrieval Delay with and without caching 2. Number of Exchanged Messages | Temperature Measurement Wireless Sensor Networks | Contiki OS and Cooja Simulator |
| [106]     | CCNx         | 6LoWPAN/RPL/UDP 1. Vanilla Interest Flooding (VIF) VS. Reactive Optimistic Name-based Routing (RONR) | Number of Consumers VS. Number of Messages Sent (With and without Caching) | Building Automation | RIOT OS |
| [36]      | NDN          | -          | 1. Number of transmission(s) 2. Number of exchanged messages VS Number of producers | Smart Home | No simulations Not mentioned |
| [36]      | NDN          | -          | No simulations Not mentioned | Light Control System (Instrumented Environment) | Not mentioned |
| [144]     | NDN          | -          | No simulations Not mentioned | Building Management Systems | Python-based Application Java-Scripting Data Visualization Application |
| Flat (and Self-Certifying) Naming Schemes for ICN-IoT |
| [136]     | CCNx         | IP based WSN | 1. Average energy consumption 2. Average delay | WSN | Contiki OS and Cooja Simulator |
| [137]     | ICN          | Not provided | Not provided | Not for low-power IoT devices | No Simulations Not mentioned |
| Attribute-based Naming Schemes for ICN-IoT |
| [138]     | ICN          | With and without ontology | 1. Storage Overhead 2. Transfer Time Consumption | Smart Hospital | C Language |
| Hybrid Naming Schemes for ICN-IoT |
| [144]     | NDN          | No Comparison | - | Vehicular Ad-hoc Networks | No Simulations Not mentioned |
| [149]     | NDN          | No naming Comparison | 1. Start-up delay 2. Playback Freezing Ratio | Multimedia Contents dissemination in VANETs | NS3 with nDnSim |
| [112]     | NDN          | 1. NLAPB 2. Simple Trie | 1. Processing Time to add prefixes 2. Processing Time to delete prefixes 3. Processing Time to search prefixes 4. Memory consumption | Vehicular Ad-hoc Networks | Not mentioned |

given to names. Application developers are free to design their own custom naming conventions. However interest is processed in a hierarchical way. Matching is performed on prefix to provide multiple responses. They used CCN for every node. Contiki OS is used with Cooja simulator to simulate physical TelosB [150] nodes. It is the first paper that implemented CCN in Contiki OS. However, only one sink (consumer) node is considered with ten to forty sensors (producer) nodes. Only static nodes are considered. Moreover, provided naming scheme is not easy to compare for a specific data as hierarchical names are long and complex to perform matching. It is suitable for IoT application having sensors deployed at fixed places (e.g., Building automation and management).

Similarly, in [36] NDN hierarchical naming scheme is modified for smart homes. Authors have provided name space specific to home related tasks. Naming scheme is designed to consist of two part: first for “configuration and initialization” for the smart home application and described by prefix “/homeID/conf/” while second part is for the “tasks” that need to be performed by smart home application and indicated through prefix “/homeID/task/”. Tasks are further specified by two named-components, type (is selected from “/action” and /sensing) and sub type (is chosen from real tasks like...
“/light, /temp, /airCond”) respectively. Name aggregation is suggested to support task aggregation to reduce number of sent messages and hence to reduce network bandwidth. But they did not provide any simulations to show how names are carried by interest and data messages. Proposed naming scheme is designed for home scenario and thus cannot be used for other IoT applications that involve mobile devices.

NDN hierarchical naming is explored and deployed for lighting automation by UCLA [142]. Contents are named according to three parts: /constant-namespaces/command/randomizer∥auth-tag. For instance, in “UetTaxila/CPED/VipLab/Light/01/ON/13:15:046FHDK”, here “UetTaxila/CPED/VipLab/Light01/” represents light numbered as “01”, located in Video and Image Processing Laboratory (VipLab) in Computer Engineering Department (CPED) of University of Engineering & Technology, Taxila (UetTaxila), “/ON/” directs to turn this light “ON” and “/13:15:046FHDK” indicates the time and corresponding computed hash of the name to ensure security of the content.

Authors in [106] have implemented NDN on IoT constraint-oriented devices for building automation. They have demonstrated the use of small names of size up to 12 bytes. They find NDN can support maximum name length up to 30 bytes. They believe that hierarchical, non-human-readable names are highly suitable for IoT smart devices while maintaining name-aggregation.

While in [114] authors believe hierarchical, human-readable names and application-specific names simplify both creation and processing tasks. NDN naming scheme is implemented to secure using ICN for UCLA campus. Designed prototype is implemented in Python and embedded in a browser-based interface. Namespace comprised of main root name followed by two sub-category names. For example, “/ndn/ucla.edu/bms/building/strathmore/data/power/<timestamp>” specifies NDN application deployed at UCLA university for university-building-management-system and fetches power data according to specified time of strathmore building located in UCLA. Moreover other sub-name spaces, “/ndn/ucla.edu/bms/user/public/key/<key-id>” directs NDN based BMS application towards public user (having multiple keys) through user specific key.

However, we argue that short-hierarchical names are suitable for IoT contents because it offers high scalability and name aggregation. Therefore, researchers need to look for the solutions to improve look-up efficiency and optimization of routing table size for IoT constraint oriented devices.

B. Flat Self-certifying based ICN-IoT Naming

ICN native approaches like DONA [110], MobilityFirst [30] and NetInf [27] follow flat, short and self-certifying names. These names can be computed using the hash of content or of any part of it and thus can be non-human-readable. Flat names can be of any fixed length and therefore simple and easy to process in routing as it take less computing resources, and consume less space while saving.

Although there are very few research attempts that explored ICN flat naming alone. We survey and present these flat naming research efforts in following paragraphs. Moreover, these efforts are not for IoTs.

In [146], authors presented ICN flat naming scheme for WSNs. Presented naming scheme have two parts: first is to identify category and second is for content. They have investigated CCN naming in Contiki OS and results indicate that proposed naming scheme outperform IP in energy consumption and delay.

In [147] authors present routing scheme based on flat naming. To provide name aggregation and efficient searching, bloom filters are used. They have introduced the concept of containers to save contents. Containers are controlled by controllers and accessed through access controllers. Flat names play a great part in routing of contents because they are short in length and this makes it easy and less complex in comparison. However, this work has not involved constraints required by low-power constraint-oriented devices, and hence, is not suitable for IoT applications.

In [151], authors survey ICN architecture naming schemes and argue that self-certifying names provide name-persistence, security-binding and universal uniqueness. Moreover, in [152] naming schemes comparison is provided and authors argue that flat names are agnostic to the structure of the data, easy to manage and seems more scalable at the network layer. Most of the work regarding flat names is conducted for name base routing [153, 154].

However, on the other hand, flat names does not provide name-aggregation which is needed for IoT contents and devices to ensure scalability. Thus, flat names can increase the routing table entries making it complex. It will increase delay to process a query and will need large space. Moreover, most of the flat names are non-human-readable, therefore to respond any query, a third-party translation mechanism will be required. IoT devices are small in memory and power, so flat names alone are not suitable for IoT contents and devices.

C. Attribute-based ICN-IoT Naming

This naming approach extract attributes of content and was used initially in CBCB [139]. This naming approach does not ensure global uniqueness of the content. Content attributes can include production date and time, content type, content location, content version number and any specific property of the content etc. Therefore, attribute-based naming support searching using easy and known key words for the content. Although it is obviously possible to find many responses against single query and its hard to find unique content in short time.

To secure contents, a routing scheme is provided in [155] using attributes of the content. In [148], attribute-based naming scheme is presented with the help of ontologies to manage contents in distributed environments. Authors claim that proposed attribute-based naming scheme provide better privacy, simple namespace management and reduces computation cost for user to determine accessibility. A hospital scenario is presented and described. In our observation this attribute-based accompanied ontologies naming scheme can outperform in IoT applications where privacy is highly needed, for example smart-health and smart-transport.
In [151], authors believe and suggest to use keywords of content created by owner as they take less time in searching while making lookup process easy.

For IoT applications, attribute-based naming can help in a perspective that IoT applications are extremely different and user can specify required content name in keywords. Attributes can be saved as keyword or hash of attributes to provide more security. Efficient advance search is only possible through attributes of the content. However, fetching unique content seems difficult with only attribute-based naming. To make this happen, other naming schemes can be combined in a hybrid fashion.

### D. Hybrid ICN-IoT Naming

Hybrid ICN based naming schemes for IoTs, refer to naming schemes combining three naming schemes or any two of them. The purpose behind combining above mentioned three naming schemes is to utilize their best features for IoT applications. Advantages of these hybrid naming schemes are manifold like improved security, better compatibility, enhanced scalability and easy name management [140]-[141].

In [143], scalable naming scheme is proposed for mobile nodes like vehicles and their produced mobile contents. Content name consists of three components:

i) Scheme, “vhn” which specifies the vehicular network or vehicular identifier,

ii) Prefix that is actually a hierarchical component, that contains information of producer (car) and details about content, and

iii) Flat part is the hash of the item, owner or signature of owner.

However, they did not provide any supporting simulations and feasibility for the proposed scheme. Moreover, the proposed naming scheme based names can be very long and suitable for VANETs only. This scheme is complex for IoT constraint-oriented devices as they can hardly forward/store such long names from/in their CSs.

In [149], hybrid naming scheme is proposed and used for multimedia contents in VANETs using ICN. Proposed naming scheme comprised of following three parts:

i) Prefix “hmn”: indicates “hierarchical multimedia naming” and hierarchical component names and used for routing and name-aggregation.

ii) Flat part is the hash computed on complete name or part of it and

iii) Attribute part is the attributes of the content.

These three parts (prefix, flat and attribute) are separated by “:” while both prefix and attribute sub-components are separated through “/”. This work is designed and evaluated for the dissemination of multimedia contents in VANETs.

In [112], authors investigated hybrid naming scheme proposed in [144] and presented their corresponding results for VANETS. Authors claimed that proposed hybrid naming scheme take less space to save more names as compared to NLAPB [156] and simple trie. They have performed simulations and results indicate that lookup time and memory management improves for VICN. Maximum prefix allowed length counted as 72 bytes. Therefore, this hybrid naming scheme is well suited for low power devices and can support IoT devices when underlying technology is IEEE 802.15.4 Zigbee (i.e., Payload size is 127 Bytes).

Through ICN-based hybrid naming, many advantages of the above described schemes (hierarchical, flat and attribute) are expected to improve further while minimizing the effects of drop-acts in case of IoTs.

### E. Summary

In this section, we have surveyed ICN based naming schemes proposed and investigated for IoT applications. We categorized ICN based naming schemes for IoT into four categories: hierarchical, flat, attribute-based and hybrid naming schemes.

Our survey indicate that for IoTs, NDN (CCN) hierarchical naming schemes and hybrid naming schemes gained more attention from research community as compared to flat and attribute-based naming schemes. We observe that main reasons behind NDN (CCN) hierarchical naming feasibility for IoTs are both simple and easy name-aggregation and better support for scalability. Moreover, human-readable hierarchically structured names with unlimited length provide faster searching as compared to other schemes and name-aggregation saves a lot of space while making routing easy.

On the other hand, ICN based hybrid naming enhances the benefits of combined naming schemes. Hierarchical component is added with the aim to provide scalable and efficient name aggregation with less number of entries to make routing process simple and easy. While flat-name component is concatenated to ensure improved security and privacy. Attributes of content are included to make fuzzy searching possible through attribute keywords.

Our survey identified that very few research studies have adopted and investigated flat and attribute-based naming separately for IoTs. Although fixed length, non-human-readable flat naming provide better security and privacy through more easy and simple computations but they do not provide better scalability, name-management and aggregation. And this is the obvious cause behind less motivation to explore flat naming for IoTs. Though, we highly suggest to use flat names to meet IoTs privacy and security requirements as a name component.

Similarly, attribute-based naming schemes alone gained less attraction from ICN-IoT research community. Attribute-based naming can assist better in advance IoT applications (for instance, an IoT application need temperature values extracted from both node 1 and 10 during the time 04:00AM to 06:00AM for any specific date from the desired area) requiring contents according to specified features. Thus, we recommend that attribute-based naming should be explored for IoTs.

However, to conclude, we recommend that hybrid naming schemes will outperform to name IoT contents and devices accompanying hierarchical, flat and attribute-based naming.

### VII. ICN-IoT Operating Systems, Simulation Tools and Languages

There are a lot of IoT Operating Systems (OS) and simulation tools that can be used for ICN-IoT. In [42] famous IoT
OSs (Contiki [157], FreeRTOS [158], RIOT [133], TinyOS [159], OpenWSN [160]) are presented under the category of open-source and closed-source (that are not available commercially). Among them, we discuss only which can be used for both IoT as well as ICN implementations. On the other hand, specific ICN simulators (ndnSim [161], ccnSim [162] and Icarus [163]) are presented in [164].

A. Contiki with Cooja Simulator

Contiki [42], [157] is an open source and flexible operating system developed at the Swedish Institute of Computer Science (SICS) in Sweden. It is very lightweight operating system for sensor nodes which are severely resource constrained in terms of power, memory, processing power and communication bandwidth. Contiki is developed in C language and is event driven. The main features of Contiki operating system include: the support of preemptive multithreading per-process and dynamic loading and unloading of code at run time. A Contiki configuration consumes 40 kilobytes of ROM and 2 kilobytes of RAM. The communication between different processes always goes using the kernel of operating system only. A full installation of Contiki operating system includes many features such as: preemptive multithreading, TCP/IP networking, proto-threads, Graphical User Interface, multitasking kernel, IPv6, web browser, simple telnet client, personal web server, and virtual network computing. Its current version is 3.0 released on August 26, 2015. Cooja Simulator [165] is the Contiki network simulator. Cooja allows large and small networks of Contiki motes to be simulated. Motes can be emulated at the hardware level, which is slower but allows precise inspection of the system behavior, or at a less detailed level, which is faster and allows simulation of larger networks. Contiki along with Cooja Simulator makes it a perfect combination for ICN-IoT related research.

B. RIOT OS

RIOT [133] is licensed as LGPL (Lesser General Public License) and open-source operating system for sensor nodes in the Internet of Things. RIOT OS is a microkernel-based operating system inherited from Fire Kernel [166], that matching the various software requirements for IoT devices. The key design objectives for RIOT OS include: energy-efficiency, small memory footprint, modularity, and a developer friendly programming interface, which make RIOT the best choice to power the widest spectrum of IoT devices. Implementation and design of RIOT has the ability to deals with the various challenges in powering of constrained devices networks. RIOT also provides the both real-time capabilities and full multi-threading. RIOT provides the C and C++ programming language supports for applications.

C. Other Simulators

NDN architecture can be simulated using its own specific ndnSim simulator. This ndnSim [161] is NS3 based simulator and provide simulation for NDN, CCN and ICN. Mini-CCNx [111] is a tool for agile prototyping of ICN based on the CCN model. This is use to build several CCN topologies, each with hundreds of nodes, with great agility and flexibility. These topologies can be run directly on laptop/desktop, in a local VM or in cloud. And the best is: the code you run on Mini-CCNx is the same code that you’ll use in a real network. This really adds a realistic behavior to your tests. Each Mini-CCNx node (host or router) runs the official Project CCNx’s so you’ll be using the official CCN implementation. ICN Simulator the Information-Centric Network Simulator developed by the University of Essex works with OMNET++ simulation environment. It provides PURSUIT architecture functionalities. It is able to simulate a large number of nodes and publisher-subscriber pairs and produce a huge amount of information, providing an insight on the new techniques introduced in the topology management of the information-centric network. Icarus [165] is caching simulator that supports multiple caching schemes and replacement schemes. It is Python-based and is a general tool to evaluate and implement ICN caching schemes. It does not support any specific ICN flavor but a simple environment to work with ICN caching.

VIII. Issues, Challenges, and Future Research Directions for ICN-IoTs

In this section, we present issues with the current solutions for ICN-IoTs and identify future research directions that need to be solved by the research community.

A. Naming

Most of the ICN based IoT naming research is conducted for CCN/NDN hierarchical naming. As CCN header is of fixed size (8 bytes) [167]. Therefore, to apply CCNx (with fixed header) for IoT low-power and constraint-oriented devices, header compression techniques can be explored to support small data packets.

However, NDN packet [169] does not have fixed length header. For small data packets (like mostly IoT applications have short length data to transmit in response of a query or to send command towards any sensor or to just acknowledge the command to or to send current state of any sensor), NDN packet formats with variable length headers provide good support for IoT applications [168].

In addition, as CCN/NDN naming follows hierarchical structure that generates long and variable length names, and these long names can be utilized to build applications that have to update their status (or sensor values) continuously. For instance, heart-beat of a specific person having any sort of cardiac disease. This can help doctor to fetch heart-beat value of that patient recorded at any specific time instant. Conversely, long names raise the problems to fit in Zigbee maximum payload of 127 bytes, so naming schemes consider this factor also. Additionally, hierarchical names are human-readable, thus, still there is need to design secured hierarchical compact naming scheme to provide original data in the case of privacy sensitive applications like smart-health.

Moreover, lookup for length-varying names is expected to be complex. Therefore, it is quite stimulating and difficult
to design such lookup system for IoT constraint-oriented devices\[169]-[170].

Furthermore, current literature investigated and proposed naming scheme for any single application, for instance in [36] and [144] ICN naming schemes are proposed for smart-home and VANETs respectively. Therefore, we stimulate ICN-IoT research community to put efforts to find and develop a naming scheme with carefully selected general, collective and public prefixes to cover (identify) and refer all IoT applications. We are still looking for a general and appropriate naming scheme that can solve all identified constraints.

B. In-Network Caching

Though identified as the major beneficial feature of ICN for IoTs, ICN-IoT caching has received a lot of attention by research community. By employing ICN caching in IoTs, ICN-IoT caching can save network bandwidth, reduce latency to get data and improve battery life of IoT devices [118].

Mostly ICN based caching schemes force to include freshness value of content while deciding about caching the content [126]-[127]-[128]. While content popularity has been included in caching decision in [131] but still there is need to explore popularity of content using simple method.

A lot of research has been conducted for caching placement strategies while most of research efforts suggest LRU as appropriate cache replacement strategy [106]-[128]-[130]. Cache coherency protocols are almost completely missing from current literature and hold a lot of potential to be explored for IoTs.

Above all, a complete caching management system is still not present in current literature. Caching management system should address the responsibilities of IoT nodes about sharing constraints to ensure privacy and security of IoT applications and about the validity of contents in a node.

C. Content Routing and Information /Content Delivery

ICN-IoTs involves data routing and forwarding mechanisms when consumer node is far-away from producer node or indirectly connected in multi-hop fashion. Mostly ICN architectures support content naming while some research efforts in ICN-IoTs support naming IoT devices [107]. To provide routing for these two different types of names, either content name can be directly used in routing or device name can be resolved through Name Resolution System (NRS) to find requested content [170].

D. Mobility

We refer mobility to both producer and consumer mobile nodes. Most of the ICN architecture designs argue that consumer mobility is inherently supported while producer mobility is not completely specified. ICN mobile data consumer simply re-issue interest message and network forwards this interest towards nearest and reliable data provider or data cached node. However, for ICN-IoTs most of the nodes can act as providers/producers of information. In IoT applications like VANETs, vehicles act as information producer about the road condition for instance, information about accident, road construction, and can even operate as information provider when these vehicles cache data to forward to other vehicles nodes. Producer mobility categorization is provided in [171], these four approaches(tracing and mapping mobile producer, data can be moved to a near stationary place or data can be regenerated form other mobile producers in that region) can be implemented for IoT scenarios. Also a proactive technique [173] can be investigated for IoTs environment. Further, to cope with provider mobility in ICN, an initial draft is presented in [174] through simple and easy to maintain anchor-less approach. We argue that this approach should be explored and can become very beneficial in IoT constraint-oriented devices having limited resources.

E. Privacy and Security

A full of potential research area is privacy and security of both user requests and data in ICN-IoTs applications. Although ICN provides authentication and access control at content level but content requests are stored in ICN intermediate routers and can be tracked by attackers [175]. Thus to maintain privacy at router level between user and producer, privacy algorithms are required. Also it is still not standardized to decide whether intermediate routers will be present in ICN-IoTs applications or not [176]. Moreover, public key infrastructure (PKI) is very complex to implement for constraint oriented devices as it requires much power in the implementation of trust management and key generation [121]. Therefore, light cryptography and light hash function can be evaluated and hence modified for constraint-oriented devices. Further, keys generation and management that include both key revocation lists and key distribution processes are still need to explore further for IoTs applications. In addition, a significant research area is control access strategies in which user authentication, their corresponding access privileges, cache access and updates are needed to be investigated for IoTs applications. Moreover, security of sensitive information, spoofing and sniffing is highly needed to explore and address as highlighted in [46].

In a nutshell, a complete mechanism ensuring both privacy and security for IoT data and applications is missing in current literature and therefore there is a strong need to design a holistic solution in this perspective.

F. In-network Computation and Cloud Computing

From IoTs perspective, in-network computation is a mechanism through which data collected from constraint-oriented sensors initially processed and later on, refined data is transmitted towards requested host. In-network computation is necessary to reduce the amount of produced data while lessening storage and high processing requirements. Other advantages of in-network computation include easy management of mobile nodes, less and refined cached data, simple data routing and forwarding and hence it can improve network-life, battery-life at the cost of simple and optimal in-network computation algorithms. A distributed in-network computation mechanism divides this task among different devices of the network and this name function networking (NFn) can improve working of
many ICN-IoT applications including smart-home and health, VANETs and smart grid [177]. This NFN further explored for IoTs and extended with scheduling algorithm [178]. Further, addition and roles of added nodes to perform in-network computation is needed to explore. Moreover, there is need to explore that how in-network computation will be performed in case of mobile nodes. Other way to perform ICN-IoT data processing and computation by employing cloud computing [179]. Clouds can share the burden of processing while providing high storage and can be used for calculating the analytics of any specific ICN-IoT application. For instance, high electricity usage can be calculated and can be seen in a any specific town of the city. Therefore, cloud assisted ICN-IoTs are needed to design that can, perform complex calculations, provide big storage and act as backup in case of mobile devices [180].

G. Content Discovery

In ICN, produced content is published by producer by placing corresponding name in nearest ICN based router and it is stored in router to fulfill further consumer queries. In ICN-IoTs, consumer requests can be satisfied in two ways: (i) content is provided from nearest router, (ii) content is fetched directly from content producer. While in second case, consumer devices may need data with specific constraints like freshness [126], [130]. To provide content accessibility in efficient way through ICN, packet formats must be specified and re-designed to cope such needs that could lead to easy content discovery and efficient delivery towards consumer. Further Interest Message and Data Message should be modified in order to support push type communication in ICN-IoTs [118]. For this, name-based aggregation can provide improved latency and efficient information lookup [107]. However, issues related to content discovery include the need to resolve: (i) How to name continuously produced contents to provide efficient look-up? (ii) How to manage content discovery efficiently in highly dynamic environments like VANETs? and (iii) How to map and search contents from named-devices corresponding to content requests efficiently?.

H. Quality of Service (QoS)

As ICN-IoTs have to drive highly heterogeneous and constraint-oriented devices, e.g., limited memory, limited battery life and specific processing unit. With these constraint-oriented devices, ICN-IoTs specific applications QoS needs, e.g., low latency for VANETs, smart city and smart grid, better scalability and high reliability for smart health, smart grid, smart house and smart personal applications, should be satisfied and are not yet considered to be explored. Therefore, there is urgent need to design QoS-aware protocols to evaluate the performance of ICN-IoTs for latency, reliability, resource-consumption and scalability. ICN has much potential to improve delay and save bandwidth to satisfy different QoS requirements. ICN striking features in-network caching, any-cast, multi-cast, adaptability to mobile devices and dynamic environments and content security at network layer reduces much efforts that needs to be done with TCIP.

I. Business Strategies and Models

It is essential as well as critical to design business models for ICN based IoTs because IoTs is known to be very advantageous and useful in our daily life. Therefore, business-strategy-makers are highly invited to put efforts to decide policies for ICN based IoTs.

We identify some main questions that are needed to be explored and answered by research community from the perspective of major entities involved in the designing of these strategies. From consumer side, researchers need to investigate following questions: What benefits will customers receive by sharing the data of their own servers, lets say, data from home server, to be cached? How will privacy of a consumer be ensured? and How much a consumer have to pay to upgrade to ICN based IoTs solutions?. Potential solutions for this can include, for instance, to provide quality data through caching, smart-home owners can get some extra free electricity or extra coaching to reduce their bills, smart-car-owners can avail free driving tips or road condition notifications in advance. From service-providers one need to look for these following questions: How ICN based IoTs will help to improve the QoS?, How it will assist to increase revenue growth? and What they would need to offer customers for caching the data?. Most importantly, every country government need to participate to decide the extent of data sharing.

However, we ar far beyond this phase of designing business models and therefore, business policy makers need to involve stakeholders, consumers and manufacturers to decide analytical consensus.

IX. Conclusions and Future Work

We discussed and presented related literature of both new paradigms IoTs and ICN. We elaborated IoTs four working phases namely: acquisition and sensing, data transmission, data processing and information management, action and utilization along with their corresponding technologies. Further, requirements and challenges to build a reliable and interoperable communication network architecture for IoTs are presented. Through this paper, we have also discussed ICN-IoT suitable features, different ICN projects for the future Internet design and their resulting ICN based network architectures for IoTs. ICN projects are discussed in terms of naming schemes, caching mechanisms and their corresponding feasibility for IoTs. Further, mapping of IoTs communication network architecture requirements against ICN striking and supporting features is presented. Moreover, we discussed ICN based solutions/architectures for IoTs to present the applicability of ICN on IoTs. Then we presented state-of-the-art literature regarding ICN naming and caching for IoTs are presented in different sections. However, we left survey of ICN based mobility and security mechanisms for IoTs as our future work and is beyond the scope for this current work. Moreover, relevant operating systems and simulators for ICN based IoTs are also discussed. In the end, we present identified research gaps that needs research community attention to build ICN based network architecture for IoTs.
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