Est. 1841 | YORK ST JOHN UNIVERSITY

Al-Khalidi, Mohammed, Al-Zaidi, Rabab, Abubahia, Ahmed, Pandey, Hari, Israfil Biswas, Md and Hammoudeh, Mohammad (2022) Global IoT Mobility: A Path Based Forwarding Approach. Journal of Sensor and Actuator Networks, 11 (3). p. 41.

Downloaded from: https://ray.yorksj.ac.uk/id/eprint/9962/

The version presented here may differ from the published version or version of record. If you intend to cite from the work you are advised to consult the publisher's version: http://dx.doi.org/10.3390/jsan11030041

Research at York St John (RaY) is an institutional repository. It supports the principles of open access by making the research outputs of the University available in digital form. Copyright of the items stored in RaY reside with the authors and/or other copyright owners. Users may access full text items free of charge, and may download a copy for private study or non-commercial research. For further reuse terms, see licence terms governing individual outputs. Institutional Repositories Policy Statement

RaY

Research at the University of York St John

For more information please contact RaY at ray@yorksj.ac.uk

Journal of
Sensor and Actuator Networks

MDPI

Article

Global IoT Mobility: A Path Based Forwarding Approach

Mohammed Al-Khalidi [1,*], Rabab Al-Zaidi [2], Ahmed M. Abubahia [2], Hari Mohan Pandey [3], Md Israfil Biswas [1] and Mohammad Hammoudeh [4]

[1] Department of Computing and Mathematics, Manchester Metropolitan University, Manchester M15 6BH, UK; m.biswas@mmu.ac.uk
[2] School of Psychology and Computer Science, University of Central Lancashire, Preston PR1 2HE, UK; ral-zaidi@uclan.ac.uk (R.A.-Z.); aabubahia@uclan.ac.uk (A.M.A.)
[3] Data Science and Artificial Intelligence Department, Bournemouth University, Bournemouth BH12 5BB, UK; hpandey@bournemouth.ac.uk
[4] Information & Computer Science Department, King Fahd University of Petroleum & Minerals, Dhahran 31261, Saudi Arabia; m.hammoudeh@kfupm.edu.sa
* Correspondence: m.al-khalidi@mmu.ac.uk

Abstract: With the huge proliferation of mobile Internet of Things (IoT) devices such as connected vehicles, drones, and healthcare wearables, IoT networks are promising mobile connectivity capacity far beyond the conventional computing platforms. The success of this service provisioning is highly dependent on the flexibility offered by such enabling technologies to support IoT mobility using different devices and protocol stacks. Many of the connected mobile IoT devices are autonomous, and resource constrained, which poses additional challenges for mobile IoT communication. Therefore, given the unique mobility requirements of IoT devices and applications, many challenges are still to be addressed. This paper presents a global mobility management solution for IoT networks that can handle both micro and macro mobility scenarios. The solution exploits a path-based forwarding fabric together with mechanisms from Information-Centric Networking. The solution is equally suitable for legacy session-based mobile devices and emerging information-based IoT devices such as mobile sensors. Simulation evaluations have shown minimum overhead in terms of packet delivery and signalling costs to support macro mobility handover across different IoT domains.

Keywords: IoT; 5G; sensors; Information Centric Networks; micro mobility; macro mobility

check for updates

Citation: Al-Khalidi, M.; Al-Zaidi, R.; Abubahia, A.M.; Pandey, H.M.; Biswas, M.I.; Hammoudeh, M. Global IoT Mobility: A Path Based Forwarding Approach. *J. Sens. Actuator Netw.* **2022**, *11*, 41. https://doi.org/10.3390/jsan11030041

Academic Editor: Mingjun Xiao

Received: 30 June 2022
Accepted: 24 July 2022
Published: 1 August 2022

Publisher's Note: MDPI stays neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Copyright: © 2022 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https://creativecommons.org/licenses/by/4.0/).

1. Introduction

The Internet has witnessed a tremendous shift in its usage as compared to the original purpose it was designed for. It has evolved from merely an experimental end-to-end host communication system intended to provide connectivity for military and scientific projects into a global content repository for content generation, sharing and access. Realizing this important role started with the conventional World Wide Web (WWW) that enabled content access through websites hosted at server machines. Information is gaining more and more importance with the emerging Internet of Things (IoT), as the majority of users are no longer interested in end host connectivity but rather in information content available [1]. Mobile content delivery has gained increasing popularity and has evolved to be the key focus of many applications that provide Generated Content. Today, services like Flickr and YouTube, in addition to social media platforms such as Twitter and Facebook, not only provide content access, but also allow mobile users to create and share their own content [1,2]. Mobile video data are the fastest growing segment of mobile traffic and is forecasted to comprise 78% of total mobile data traffic by 2023 [3]. The accelerated growth will be encouraged by wide adoption of live video, Augmented Reality (AR), and Virtual Reality (VR) [4]. On the other hand, the significant progress achieved in mobile technologies has allowed users to enjoy Internet services during movement, which is facilitated through the use of mobility management protocols. Mobility management is a challenging task

since it largely affects users' experience with respect of preventing frequent disconnections and ensuring session continuity [5].

Realizing this information centric and mobile usage of the Internet has raised various architectural challenges, many of which have not been handled efficiently by the Internet architecture [6]. The mismatch between information dominance and the host-to-host communication model of the Internet has led to application specific solutions for content delivery which are very costly and often inefficient. Popular examples include Domain Name System (DNS) redirect which relies on maintaining multiple IP addresses to a single Fully Qualified Domain Name (FQDN) and mapping the FQDN to one of the IP addresses, depending on the location of the IP addresses. DNS redirect selects a nearest Point-of-Presence (PoP) to the local DNS point that is not necessarily closest to the client. This results in some scenarios having highly inefficient mappings, thereby degrading the end-to-end QoS while increasing load inside the network [7,8]. Another example is IP multicast that offers point-to-multipoint delivery for group communication applications on the Internet. However, its support for content delivery suffers from a lack of scalable access control mechanisms, address allocation, and network management [9]. In terms of mobility, the IP host-to-host communication paradigm that ties the end hosts address to its location prevents a moving host from naturally maintaining a single identifier when attaching to different points in the network. Therefore, the moving host is exposed to intermittent and, possibly, opportunistic connectivity. Such an approach does not achieve continuous connectivity while on the move, which is becoming an increasingly important requirement. The problem has generally been addressed by using IP tunnelling through a central anchor point, which tracks the IP addresses of moving hosts and instructs the access gateways to provide the same IP address to the same host [10–12].

In effect, the aforementioned solutions help to partially overcome the limitations of the Internet architecture; however, they do not provide a holistic solution to the problem. For example, they suffer from scalability constraints, as they create bottlenecks in the network. This is due to sub-optimal routing via the anchor point, which is often termed as "dog-leg" routing [13].

In this paper, we present the result of a mobility management approach that utilizes path forwarding architectures. Solutions such as Line Speed Publish/Subscribe Inter-Networking (LIPSIN) [14], Stateless Multicast Switching in Software Defined Networks [15], Bit Indexed Explicit Replication (BIER) [16], and IP-over-ICN [13] rely purely on path information for end-to-end forwarding of packets instead of relying on host address-based communication with routing information distributed over various network elements. In these path-based approaches, path information can be stored in the forwarded packet (using Bloom filters) and forwarding is done by performing a simple set membership test to deliver a packet traversing the network to the final destination. Therefore, these architectures allow for efficient mobility management, specifically macro mobility support, which is becoming increasingly important for many IoT devices that need to roam across different domains. In this paper, evaluation results using an IP-over-ICN embodiment have shown promising results in terms of the packet delivery cost and signalling costs required to support macro mobility across different IoT domains.

The rest of the paper is structured as follows: Section 2 provides an overview of mobility management solutions in different access technologies, while Section 3 presents the related work. Section 4 introduces mobility over path forwarding architectures, and presents the proposed macro mobility handover solution. The simulation and cost evaluation results are presented in Section 5, and, finally, the paper is concluded in Section 6.

2. Mobility Management Solutions in Different Access Technologies

In this section, we review the most widely applied mobility management solutions in the two main mobile access technologies (wireless and cellular) and summarize the most important factors that distinguish each one.

2.1. Wireless IP Networks

Mobile IP in its two versions MIPv4 [10] and MIPv6 [12] is the Internet Engineering Task Force (IETF) standard mobility solution that is designed to allow Mobile Nodes (MNs) to keep their IP address while moving. This enables forwarding traffic destined to MNs when they change their point of attachment to the network, hence providing mobility support. Mobile IP is a host-based mobility solution, where the MN takes part in the mobility management process. The solution has witnessed several enhancements leading to the Proxy Mobile IPv6 (PMIPv6) [17,18]. PMIPv6 is a network-based mobility management solution that separates the mobile node from the involvement of the handover procedure as compared with host-based mobility protocols [19,20]. PMIPv6 promises easier deployment and better handover performance and is aimed at accommodating various mobile access technologies such as WiMAX, 3GPP, 3GPP2, and WLAN.

PMIPv6 introduces two network entities, namely the Local Mobility Anchor (LMA) and the Mobile Access Gateway (MAG) as shown in Figure 1. The LMA is responsible for maintaining the MN's reachability and acts as a topological anchor for the MN's home network prefix(es). The MAG has the responsibility of performing mobility management on behalf of the MN and resides on the access link where the MN is attached [21]. It detects the MN's movement to and from the access link and coordinates with the LMA to make sure that the MN will be able to obtain the same address configuration from its home network prefix(es) even after connecting to a different MAG with the PMIPv6 domain [17].

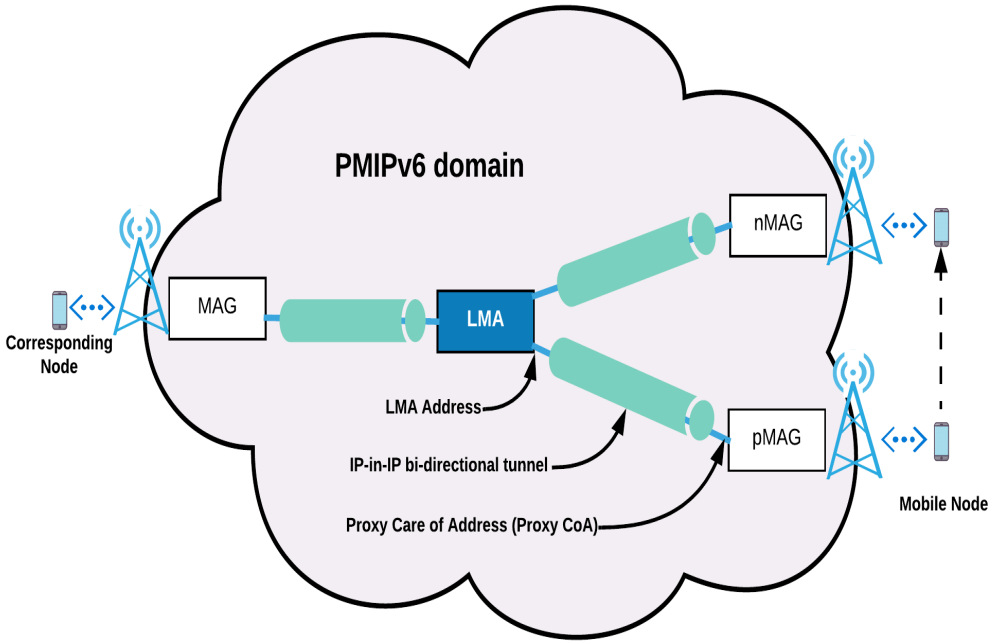

Figure 1. Proxy mobile IPv6 domain.

In PMIPv6, the LMA discovery can be achieved as follows: First, the MAG receives the LMA's Fully Qualified Domain Name (FQDN) from the Authentication, Authorization, and Accounting (AAA) infrastructure during the network access authentication. Then, the MAG resolves the FQDN to the LMA's IP address through a DNS lookup.

Upon an IP handover from one MAG to another, the LMA is notified about the MN's change of location, and the MN's binding at the LMA is updated according to the following procedure. The previous MAG (pMAG) sends a Proxy Binding Update (PBU) message to the LMA to de-register the MN, and the new MAG (nMAG) sends a PBU message to the LMA to register it. The LMA replies to each of the PBU messages by a Proxy Binding Acknowledgement (PBA) message. All the data traffic of the MN passes through the LMA and a bi-directional tunnel is established between the LMA and the MAG that serves the MN [19]. An advancement of PMIPv6 is the Proxy-Based Fast Mobile IPv6 Protocol

(PFMIPv6) by IETF [22], where an additional bidirectional tunnel is established between the previous and new MAG to tunnel packets meant for the MN during handover as shown in Figure 2. There are two modes of operation in PFMIPv6: (a) a predictive mode where the tunnel between the serving and the target MAG is established prior to the MN's attachment to the New MAG, and (b) a reactive mode where tunnel establishment takes place after the MN attaches to the New MAG [23].

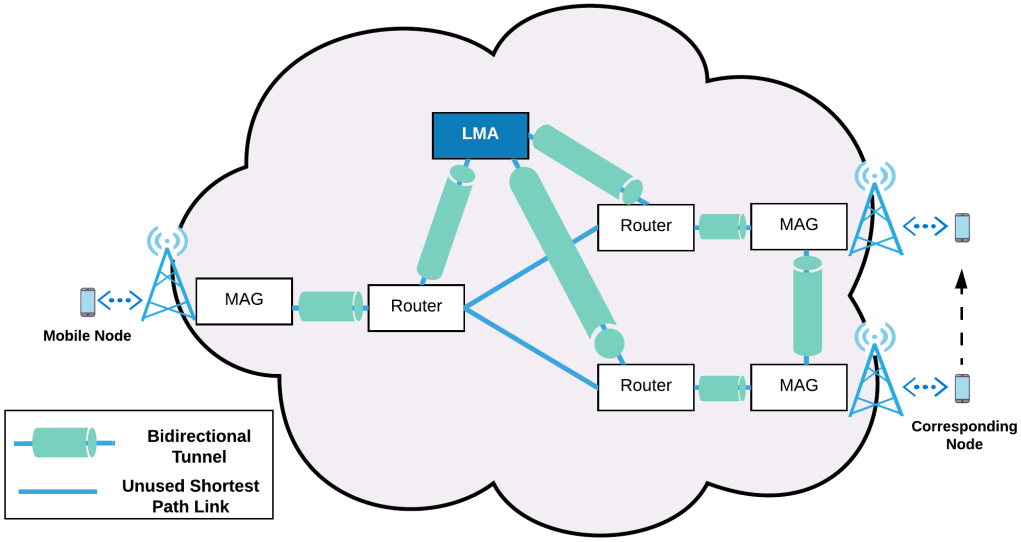

Figure 2. Seamless handover in PFMIPv6.

2.2. 5G Networks

3GPP specifies the General packet radio service (GPRS) Tunneling Protocol (GTP) [24] to support mobility in cellular networks by anchoring user plane and control plane traffic at specific core entities. Figure 3 shows the overall 5G network architecture, including the network elements and the standardized interfaces. In 5G networks, user plane traffic is anchored at the User Plane Function (UPF) and control plane traffic at the Access and Mobility Management Function (AMF) [25]. Handover is performed: (a) via the Xn interface, which provides a direct connection between gNBs, or, (b) via the N2 interface between the gNB and the AMF, when Xn handover is not possible (e.g., new radio conditions, load balancing, no Xn connectivity to the target gNB, etc.). The serving gNB decides when to trigger a handover process, which consists of three phases (handover preparation, execution, and completion) based on measurement reports received from the MN that include among other information, indicators of the radio signal strength of the serving and neighbor cells as received by the MN. When handover is performed over the Xn interface, downlink packets are delivered over the interface from the serving gNB to the target gNB during handover execution phase in order to prevent packet loss [26].

In both wireless and cellular mobility solutions described above, anchoring is used to overcome the location dependent end-to-end communication paradigm by tracking the address of a moving host, and maintaining a tunnel to its new location for packet delivery. This form of "dog-leg" routing introduces tunnelling overhead and sub-optimal routes with an overall increase in traffic and latency.

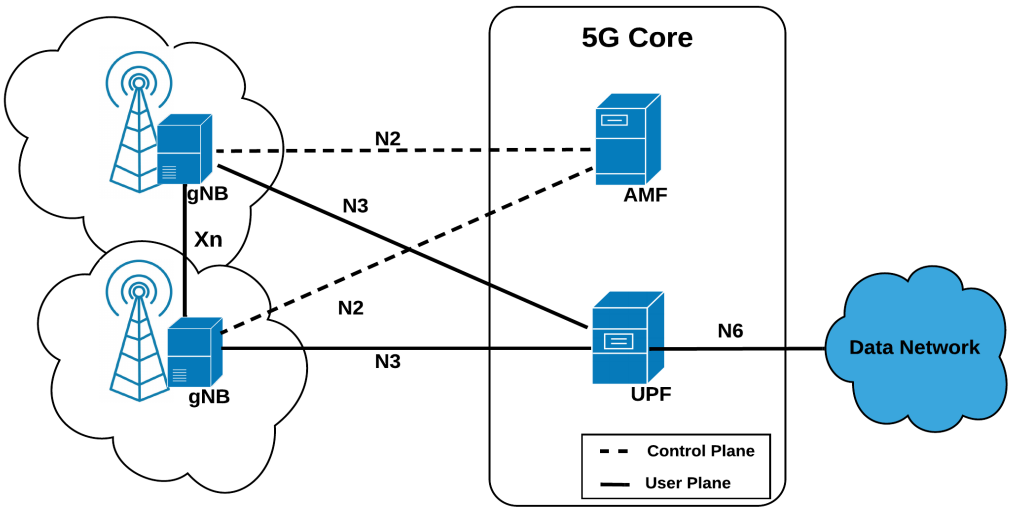

Figure 3. 5G network elements and interfaces.

3. Overview of Related Work

Fueled by the proliferation of media capable smart phones, the emergence of social networks, and the plethora of IoT sensory applications, there has been an increasing demand for uninterrupted mobile services. A large number of research efforts in the literature have aimed to realise this objective with solutions focusing on Information Centric Networks (ICN). The main drawback of such proposals is that the network stack of every mobile device, together with the application network interface code, have to be replaced [27,28]. Here, we look at the most relevant of these efforts.

The authors in [29] present a blueprint for optimizing mobility support in ICN using the PURSUIT architecture [30]. They demonstrate that the ICN mechanisms supported in PURSUIT, along with smartly placed in-network caches, enable the architecture to handle both mobile and fixed devices in an efficient uniform way. Mobile nodes can simply reissue subscriptions for information after handover and the network may direct these subscriptions to nearby caches rather than the original publisher.

In [31], the authors propose a mobility management scheme for Content Centric Networks (CCN) that aims to provide faster service access and lower routing overhead. The solution presents a path redirection scheme, where all communications are done via a home domain content router. The mobile content source informs its home domain content router of its movement by delivering a prefix update message. Evaluation results show lower network convergence time and lower service disruption as compared to basic CCN; however, triangular routing is introduced by tunneling-based redirection.

An anchor-less solution to manage micro-mobility of content producers (Publishers) via a name-based CCN/NDN data plane is proposed in [32]. The authors focus on Publisher mobility, given that Subscriber mobility is supported in ICN by design (in virtue of its connectionless pull-based communication model). The authors set up a comprehensive simulation environment to evaluate and compare their solution against existing solutions, including a realistic trace-driven car-mobility pattern under a 802.11n radio access. The results show that the proposed solution satisfies its objectives while equalling or outperforming the performance of existing alternatives, both in terms of user related metrics (e.g., loss, delays) and network related metrics (e.g., signaling overhead, link utilization). Similarly, the authors in [33] describe an initial proposal for an anchor-less approach to manage producer mobility via Interest Updates/Notifications in the data plane, even in the presence of latency-sensitive applications. They detail the different operations triggered by producer movements and define a timely forwarding update mechanism populating a Temporary Forwarding Information Base FIB (TFIB) at routers relaying former and current producer location.

The authors in [34] present a service-driven mobility support architecture for Information Centric Networks that provides seamless mobility as an on-demand network service. This service can be enabled/disabled based on network capabilities or resource availability. The architecture proposed in [34] relies on the ID/Locator split on ICN namespaces to support the use of persistent names and avoids name reconfiguration due to mobility. The proposed solution has been implemented over a service-centric CCN platform and showed promising results towards achieving seamless handover.

The authors in [35] present a multiple-level proxy caching model in an ICN architecture, where content requests from mobile subscribers and the corresponding items are proactively cached to these proxies at different levels. The caching model selects the appropriate subset of proxies and supports distributed online decision procedures in terms of the trade-off between delay and cache cost. Simulation results show significant savings in total costs for both full caching and no caching scenarios.

In [36], the authors propose an ICN based mobility solution with a special focus on network mobility, where network segments/domains comprising of various networking nodes, consumers and producers can also experience mobility. Evaluation results show that the proposed solution significantly reduces the amount of signalling traffic, routing updates, and path inflation compared to existing solutions while ensuring connectivity for mobile nodes.

In [37], the authors present a device-level information centric networking architecture that is able to perform intelligent content distribution operations according to necessary context information on mobile user mobility and content characteristics. The authors further introduce device-level online content caching and offline helper selection algorithms in order to optimize the overall system efficiency, which is demonstrated through simulation experiments and modeling.

In [38], the authors design a mobility-aware proactive caching scheme in ICN to provide delay-sensitive services on Internet of Vehicle (IoV) networks. The real-time status and interaction of vehicles with other vehicles and Roadside Units is modeled using a Markov process. The authors apply Mobility aware proactive edge caching decision that maximizes network performance while minimizing transmission delay. Numerical simulation results show that the proposed scheme outperforms related caching schemes in terms of latency by 20–25% and by 15–23% in terms of cache hits.

In [39], the authors propose a novel vehicle tracking-based Data packet forwarding scheme (VTDF) to improve the successful delivery rate of Data packets in Named Data Network (NDN) based Vehicular Ad Hoc Networks (VANETs). In this approach, the urban road structure is divided into complex multi-junction and straight lane scenarios and Data packets are forwarded according to vehicle movement information. Simulations indicated that this vehicle tracking scheme provides a lower average data transmission delay, shorter handover delay between roadside units, and higher data delivery rate for Consumers compared to the standard methods.

In [40], the authors propose a reinforcement learning-based data source selection scheme (RLSS) for efficient High Definition (HD) map distribution in vehicular named data networking (NDN) scenarios. The proposed scheme aims at seeking the best data source (roadside infrastructures or nearby vehicles) in accordance with the map data requests. Specifically, the scheme adopts a deep reinforcement learning-based architecture to learn a neural network as an agent to make the decision of data source selection. The authors have demonstrated through extensive simulations that RLSS can significantly improve the transmission performance in terms of delay, throughput, and packet loss when compared with state-of-the-art data source selection schemes.

All of the above have shown promising results with using an information-centric approach, albeit with the requirement to change the end point networking stack. On the other hand, there are other proposals that enable applications running on IP protocol stacks to utilize ICN networks. They can be summarized as follows.

A general purpose tunneling protocol (IPoC) is presented in [41], and uses Named Data Network (NDN) semantics and cellular communication as the driving example. IPoC is transparent to the IP applications on either end that remain unchanged. The authors compare their protocol performance with native IP and show that IPoC protocol overhead and performance degradation is minimal. In return, they show how NDN and IPoC can bring ICN benefits to 5G mobile networks by simplifying the mobility plane and introducing intelligent functionality.

The authors in [42] present a TCP/ICN proxy capable of carrying TCP traffic between TCP/IP endpoints over NDN/CCN. They evaluate several alternative TCP/ICN proxy designs in a simulation environment. Performance measurements of their proxy design using both simulation and real implementation demonstrate that TCP can traverse ICN networks without significant additional delay or loss of goodput.

The authors in [43] identify a common design space for providing IP and NDN mobility support and propose two knowledge-driven mobility support approaches. These approaches exploit knowledge such as network topology and movement trajectory to tweak the network for better mobility performance. Experiment results show that the knowledge driven approaches significantly improve mobility support performance.

The authors in [44] propose a hybrid architecture to support video streaming simultaneously over TCP/IP and Named Data Networking (NDN)-based architecture via operating system and networking virtualization techniques. In addition, to relieve users from the burden of installing a new protocol stack (in the case of NDN) on their devices, the authors developed a lightweight solution in the form of a container that includes the network stack as well as the streaming application. A propotype evaluation demonstrates that, in the case of live streaming, NDN achieves better QoE per client than IP and can also utilize higher than allocated bandwidth through in-network caching.

Notably, the proposals above deploy NDN/CCN cores that introduce large stateful Pending Interest Tables (PITs) that keep track of information requests, hence, imposing scalability challenges.

4. Mobility over Path Forwarding Architectures

MN movement within a single operator domain from one Network Attachment Point to another is known as micro mobility or in other words intra-domain mobility. On the other hand, MN movement across two different domains is known as macro mobility or inter-domain. To this end, micro mobility management using a path forwarding architecture is described in detail in [13], where interested readers are referred to. However, it forms the foundation of our macro mobility management solution introduced in this paper; therefore, a brief description is provided here.

In the proposed path forwarding architecture, we consider four types of entities that take part in any mobility scenario: an MN, a network attachment point (NAP), a Path Computation Element (PCE), and a Forwarding Element (FW). The MN connects wirelessly to an NAP that provides interconnection with a wider distribution network. The PCE determines a path of communication through the network on behalf of a MN or NAP. Optionally, the PCE can also include an information naming function (INF) that provides a method of storing identities (e.g., services, names, and/or IP Addresses) and matching interests. This can help in identifying different services, flows, or bearers for communication. The FW simply forwards information from the MN to the destination using a specific Forward Identifier (FID) generated for this transmission. All the NAPs receive their specified FIDs and populate a local table containing the complete set of FIDs required to reach any other NAP in the network. The first link connecting the MN to the network, e.g., the Network Attachment Point (NAP), is based on the IP protocol, while the NAP serves as an entry point to the core network, which is forwarding based. In the proposed architecture, IP simply becomes a service enabled through the forwarding core, and IP addresses are translated into identifiers used directly for routing.

The proposed handover process is described using the example shown in Figure 4 for MNs with IP stack and connectivity; however, the solution is equally applicable using any other identifiers. Initially, the MN attaches to NAP A (collocated with gNB A) and performs Link Layer Connectivity and IP Address Establishment. The MN can acquire a global IPv6 address using the Stateless or Stateful address auto configuration procedures (or even manual address configuration) as specified in [17]. NAP A then extracts the source and destination IP addresses from the first packet sent from the MN towards the corresponding node (CN). NAP A sends a forwarding path request including the identifiers (IP addresses) to the PCE. The PCE (or possibly the INF) keeps track of all MN identifiers in the network and links every identifier to its corresponding attachment NAP. Next, the PCE uses its knowledge of the network topology and end-user identifiers to calculate and send the required Forward Identifier (FID) to NAP A, which at this point is ready to forward packets to the CN at NAP B (Collocated at gNB B). The process described above is only for one side of the communication; therefore, the same should happen at the CN's side in order to forward packets from the CN towards the MN. Crucially, this process only happens once for new communication flows, and not for every packet.

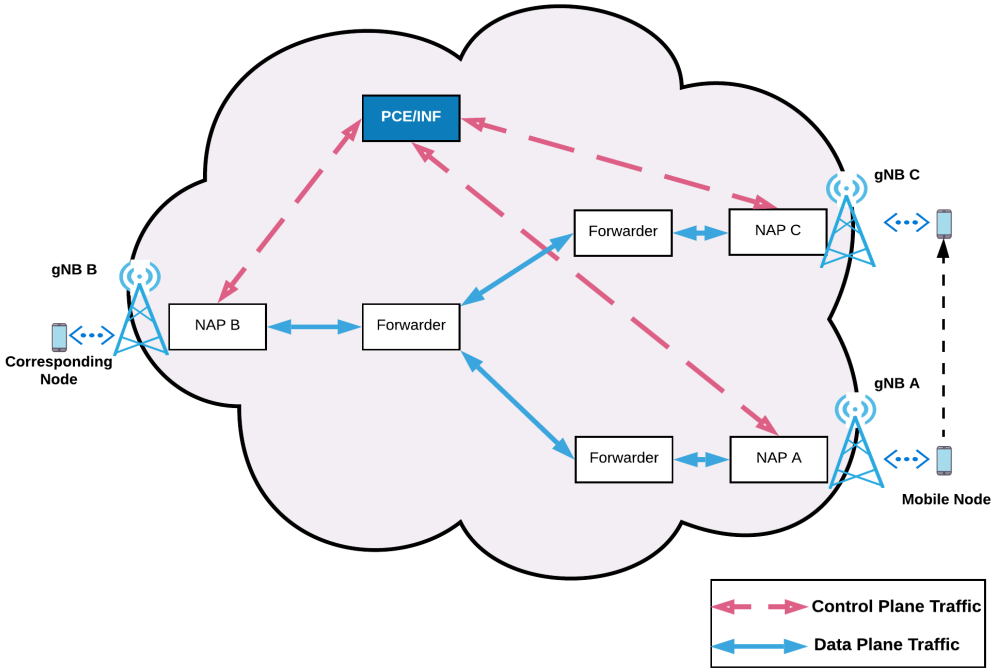

Figure 4. Micro (intra-domain) mobility handover in a path-based forwarding architecture.

Upon handover, NAP A notifies the PCE of MN A's departure so the latter can expect the MN's connection from a different NAP. MN A then attaches to NAP C (collocated with gNB C) and re-establishes Link Layer Connectivity and IP Address allocation. This triggers NAP C (upon receiving the first IP packet from MN A) to extract the source and destination IP addresses, and send a forwarding path request including the identifiers (IP addresses) to the PCE. Then, the PCE can use its knowledge of the network topology and end-user identifiers to calculate and send the required Forward Identifier (FID) to NAP C which at this point is ready to forward packets to the CN at NAP B.

Macro Mobility Support

The proposed macro mobility solution in a path-based forwarding architecture is presented using an IP-over-ICN embodiment [45]. This follows a gateway-based approach and provides the necessary path-based forwarding described in Section 4 above. The access from the MN to the network uses existing IP-based protocols, such as HTTP, CoAP, TCP, or IPv4/v6, while the NAP serves as an entry gateway point to the ICN network and

maps the chosen protocol abstraction to ICN. The ICN core employs a Publish–Subscribe paradigm [45] for information dissemination that names information at the network layer, arranging individual information items into a context named scoping. Relationships between information items and scopes are represented as a directed acyclic graph of which leaves represent pieces of information and inner nodes represent scopes. Each node in the graph is identified with its full path starting from a root scope. In the context of an IP-over-ICN architecture, the ICN names are simply the IP addresses of the MNs or the fully qualified domain names (FQDNs) used by the end-systems. The IP-over-ICN solution uses Publish/Subscribe (Pub/Sub) semantics for carrying IPv4/v6 datagrams over the ICN network. As described earlier, the INF (referred to as the Rendezvous in the IP-over-ICN embodiment) looks after mapping names (IP address or FQDNs), and the PCE (referred to as the Topology Manager in the IP-over-ICN embodiment) creates the forwarding FIDs. Note that the FID encodes a delivery tree for the communication [13]. Figure 5 presents an example of macro mobility handover in IP-over-ICN, where MN A moves from Domain 1 to Domain 2 while communicating with the CN that exists in Domain 1.

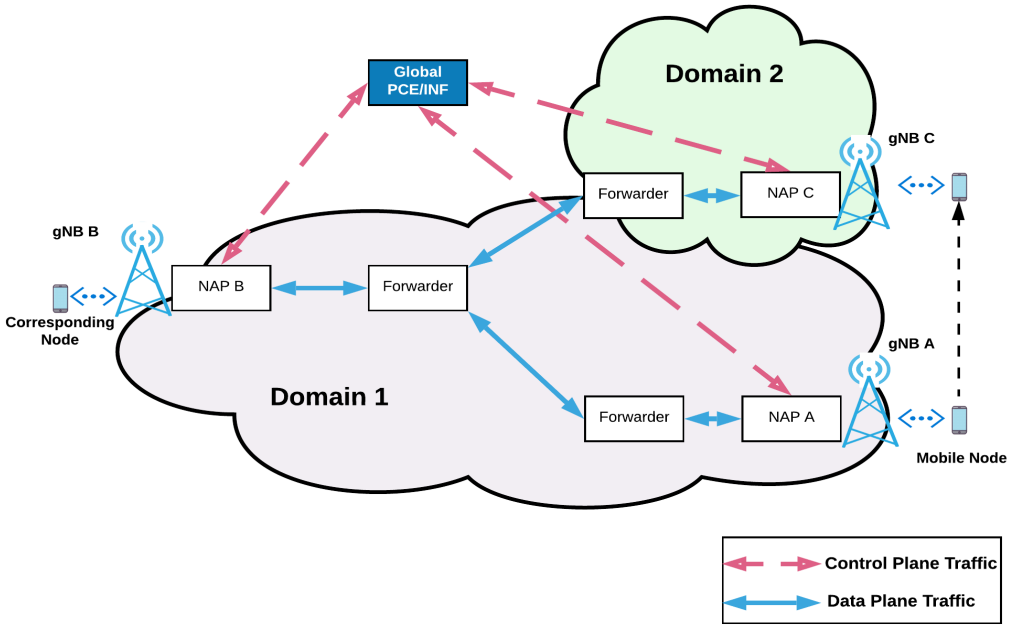

Figure 5. Macro (inter-domain) Mobility Handover in a path-based forwarding architecture.

To support both micro and macro mobility management (referred to in this paper as global mobility management), we propose the namespace shown in Figure 6, where every MN's globally unique EUI48 identifier is represented as a scope identifier under the mobility namespace. Any IP address assigned to a MN will be represented as an identifier that is multi-homed to both the mobility root scope (M) and the EUI48 scope specific for that MN. This allows for two publication/subscription possibilities for a specific IP address. The first is without the EUI48 identifier when publishing a request for a destination IP address where the EUI48 identifier is unknown (e.g., /M/IP1), and the second is with the EUI48 identifier when subscribing to the MN's own IP address where the EUI48 identifier is known (e.g., /M/EUI48/IP1).

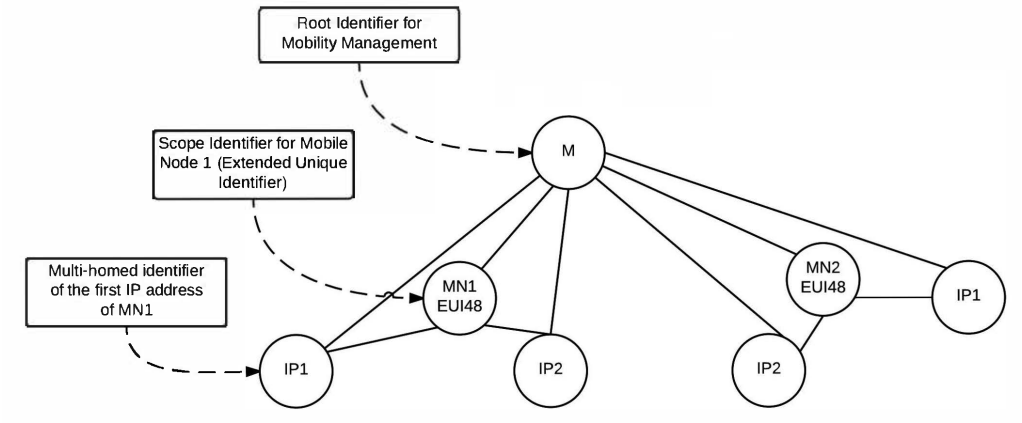

Figure 6. Mobility namespace.

We also propose that the Rendezvous (RV) maintains a mobility binding list whose rows represent MN EUI48 identifiers and columns represent corresponding IP addresses learnt by the Rendezvous for that MN. The last IP address in the list is the latest IP address allocated to the MN. These relations are learnt from the subscription messages sent from every MN each time it attaches to an NAP and requests communication through the ICN network. Figure 7 shows a basic 2 Node initial session establishment scenario with mobility support. In this scenario, MN A and B attach to NAP A and B respectively completing Link Layer Connectivity and IP Address Establishment. NAP A then extracts the source and destination IP addresses from the first packet sent from MN A towards MN B and publishes scope (/M/IP-B 1) on behalf of MN A to request communication with MN B and implicitly subscribes to scope (/M/EUI48-A/IP-A 1), so it can receive any information directed to MN A. On the other hand, NAP B publishes scope (/M/IP-A 1) on behalf of MN B to request communication with MN A and implicitly subscribes to scope (/M/EUI48-B/IP-B 1), so it can receive any information directed to MN B. Upon receiving NAP A and B's publication and subscription messages, the Rendezvous updates its mobility binding with MN A and B's EUI48 and corresponding IP address that are extracted from the subscription messages. It also publishes scope /M/EUI48-B/IP-B 1 on behalf of MN A, and scope /M/EUI48-A/IP-A 1 on behalf of MN B, and then matches the corresponding publications and subscriptions for those scopes. The Rendezvous then triggers the Topology Manager (TM) to create new FID's both ways from MN A to MN B and vise versa. The TM creates and forwards the new FID's to the MNs, which will then be able to stream data packets between each other.

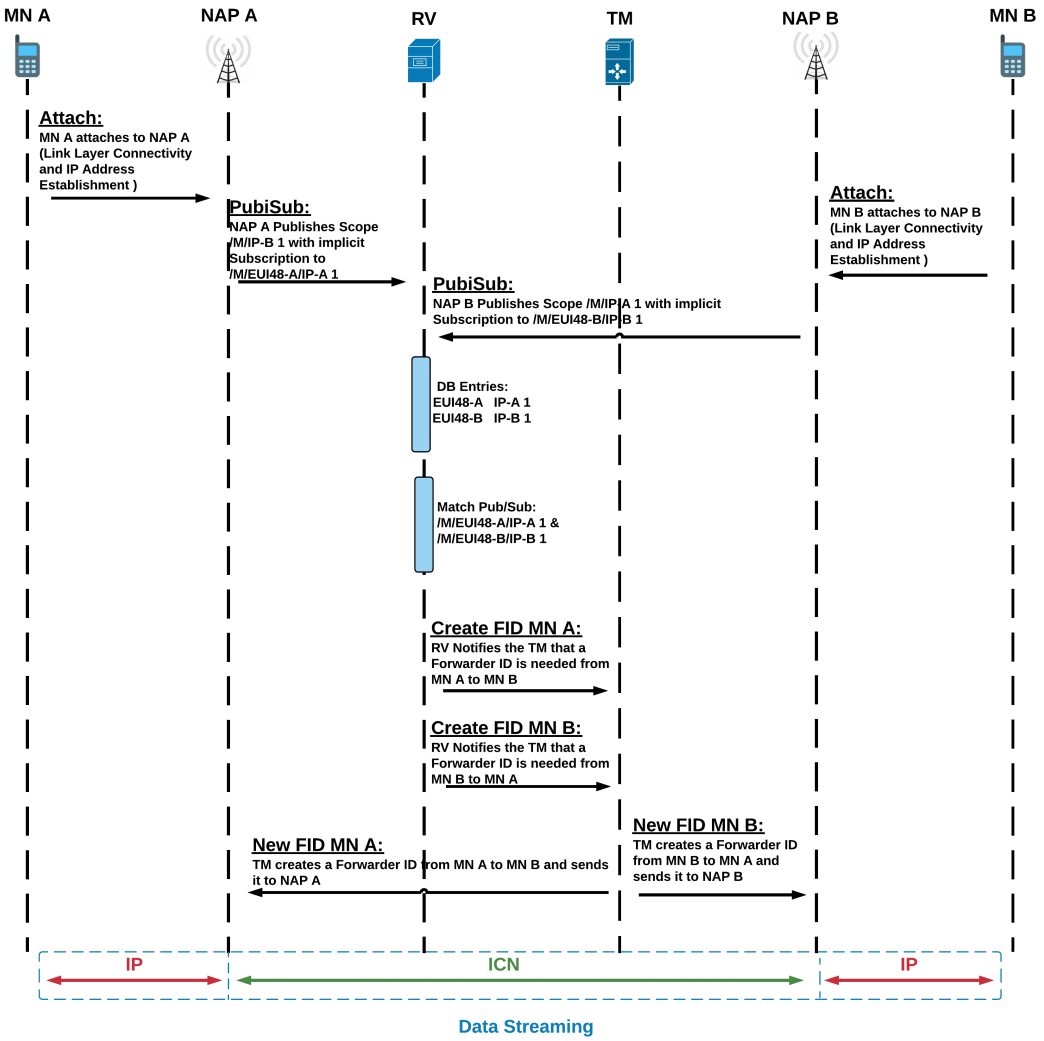

Figure 7. Sequence diagram of session establishment with global mobility support in IP-over-ICN.

Figure 8 shows the sequence of messages when MN A changes its point of attachment to a new network domain (domain 2). When MN A de-attaches from NAP A, NAP A then un-publishes scope (/M/IP-B 1) with implicit un-subscription from (/M/EUI48-A/IP-A 1) on behalf of MN A. At this point, the RV keeps the entry in its binding list that has IP-A 1 as the last known IP address for MN A. Supposing MN A then re-attaches to NAP C in domain 2, NAP C publishes Scope (/M/IP-B 1) on behalf of MN A with implicit Subscription to (/M/EUI48-A/IP-A 2), which includes its new IP address (IP-A 2) allocated by the new domain. At this point, the RV updates its binding entry for MN A to include IP-A 2 as the latest IP address and also keeps IP-A 1 in the list in case it receives any publication request towards MN A's previous address. It also instructs the TM to update the FID's of MN A and MN B accordingly. This way, session continuity is maintained between the two mobile nodes even when IP addresses change. It is worth noting that, if an IP address that was previously added to the RV binding list is reassigned to a new MN, then it would be removed from the old MN entry and added as a new IP for the new MN, keeping only one instance of the IP address on the binding list at any time.

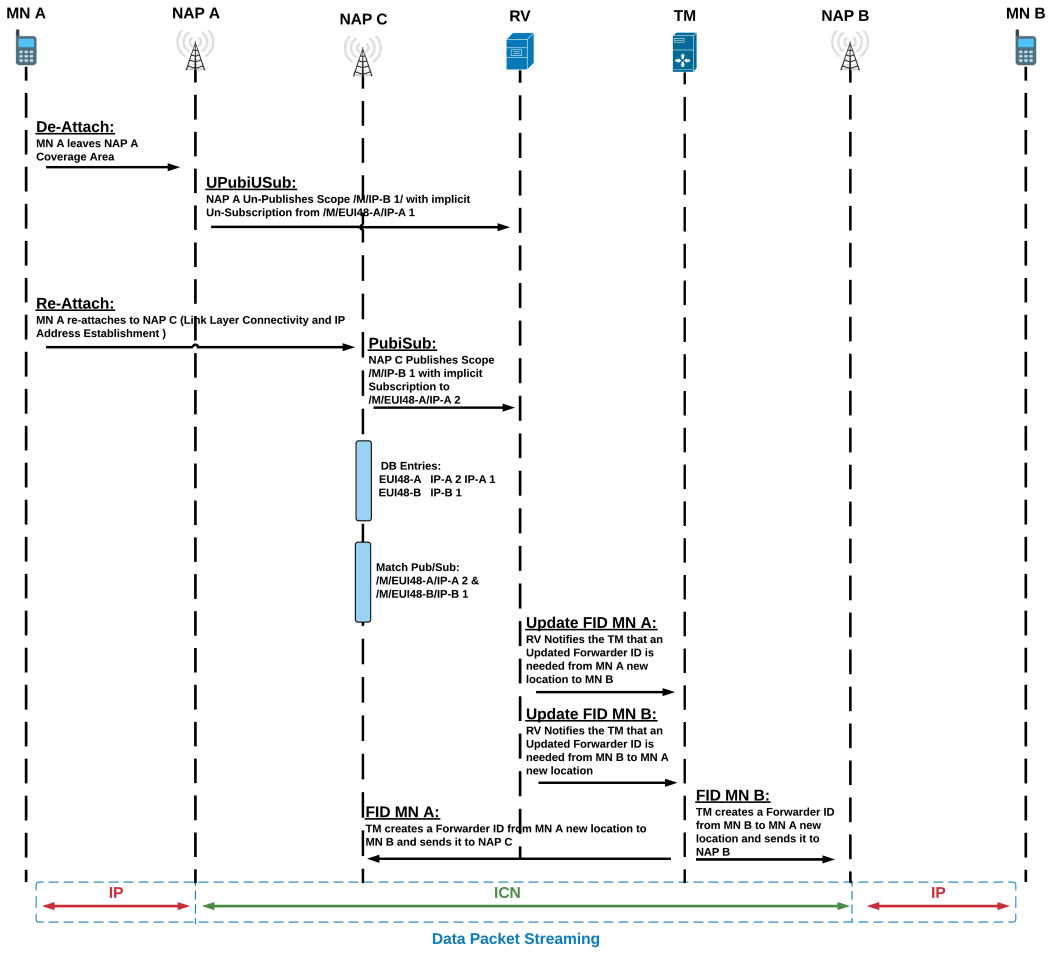

Figure 8. Sequence diagram of handover with global mobility support in IP-over-ICN.

5. Simulation and Cost Evaluation

The cost of the proposed global mobility solution using an IP-over-ICN embodiment is evaluated using a packet level discrete time event simulator built in R language. The built simulation environment has been used to investigate the mobility costs (mainly mobility signalling and packet delivery costs). We considered a sample IoT network of one TM/RV and 148 nodes across two network domains. Each domain consists of 24 core forwarder nodes and 50 gNBs. Random geometric networks have been used to represent network topologies to ensure spatial homogeneity of the positions of the gNBs. Two network scenarios have been simulated, one with micro mobility only, and another with global (micro and macro) mobility. NAPs have been assumed to be collocated with the gNBs. We assume that NAPs have a circular coverage area of radius between 500 and 1500 m with average connection degree of four neighbors each. A random waypoint mobility model has been used to capture user/node mobility at different speeds ranging from pedestrians moving at 3 mph to vehicles travelling at 70 mph. Initial locations are decided using a uniform random distribution. In our traffic model, we assume that all the IoT MNs in the network are using different protocols such as HTTP, CoAP, TCP, or simply IPv4/v6 to exchange data with an arrival rate of 1 Mbps following a Poisson distribution. We also assume ICN FIDs and scope/ID lengths of 256 bits each. A list of the simulated mobility messages and their corresponding sizes is shown in Table 1.

Table 1. List of mobility messages and their sizes [13].

Description	Size in Bytes
Unpublish with Implicit Unsubscribe (UPubiUnsub)	166
Publish Request	160
Start Publish	166
Publish with Implicit Subscribe (PubiSub)	166
ICN payload packet header	96

5.1. Packet Delivery Cost Evaluation for Global vs. Micro Mobility Support

Figure 9 presents the results of a simulation run of 1800 s for micro vs. global mobility in IP-over-ICN. Fifty MNs were simulated to move freely and randomly within each network domain (in case of micro mobility) and across domains (in case of global mobility). Due to the high dependability of the mobility costs on the network topological aspects, the latter are taken into account when evaluating the Packet Delivery Cost (PDC) and Signalling Cost (SC) of the solution. Therefore, PDC and SC are evaluated in Bytes × Hops/Sec over the simulation period. The figure shows that the packet delivery cost (PDC) for IP-over-ICN to support global mobility is approximately 4×10^6 Bytes × Hops/Sec compared to 3×10^6 Bytes × Hops /Sec for micro mobility support. The slight increase shown in the packet delivery cost is due to the inevitable fact that path lengths (and hence packet delivery costs) increase when communication is established inter-domain rather than intra-domain.

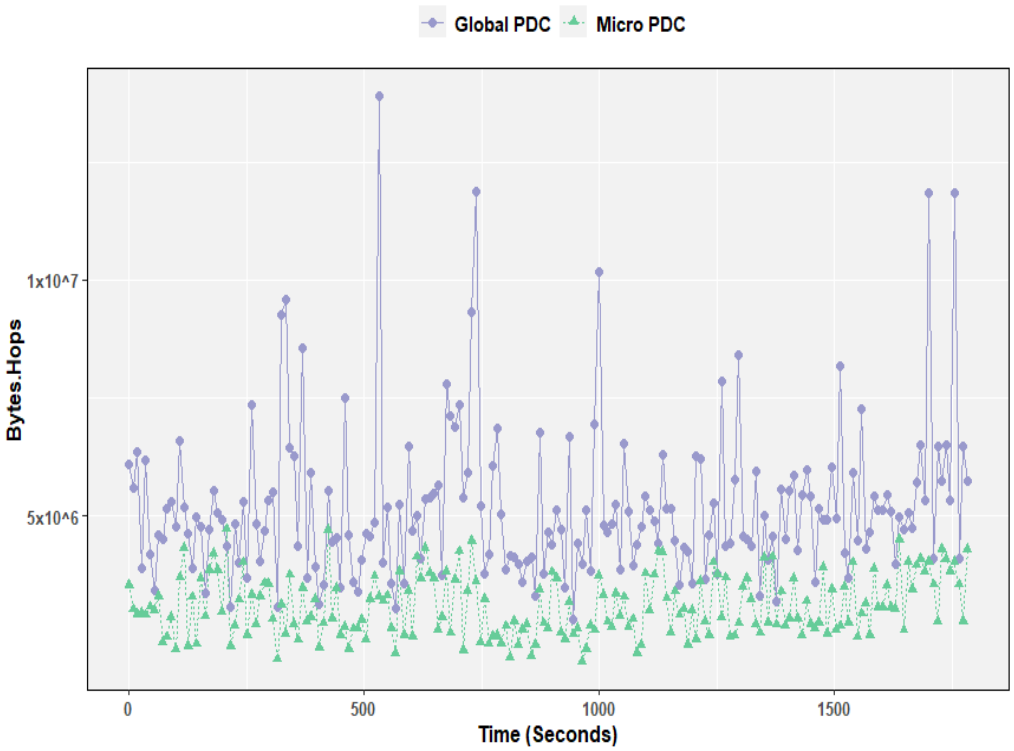

Figure 9. Packet delivery cost (PDC) for IP-over-ICN micro and global mobility support.

5.2. Signalling Cost Evaluation for Global vs. Micro Mobility Support

Figure 10 shows the signaling cost (SC) for IP-over-ICN to support micro and global mobility for MNs with different speeds over a simulation run of 1800 s. The figure shows that IP-over-ICN incurs an average SC of approximately 5.5×10^3 Bytes $\times$ Hops/Sec to support global mobility, compared to 4.2×10^3 Bytes $\times$ Hops/Sec for micro mobility support. The difference shown in signalling cost is due to the increased distance between the TM/RV and the NAPs/gNBs that manage the signalling on behalf of the MNs in the inter-domain scenario.

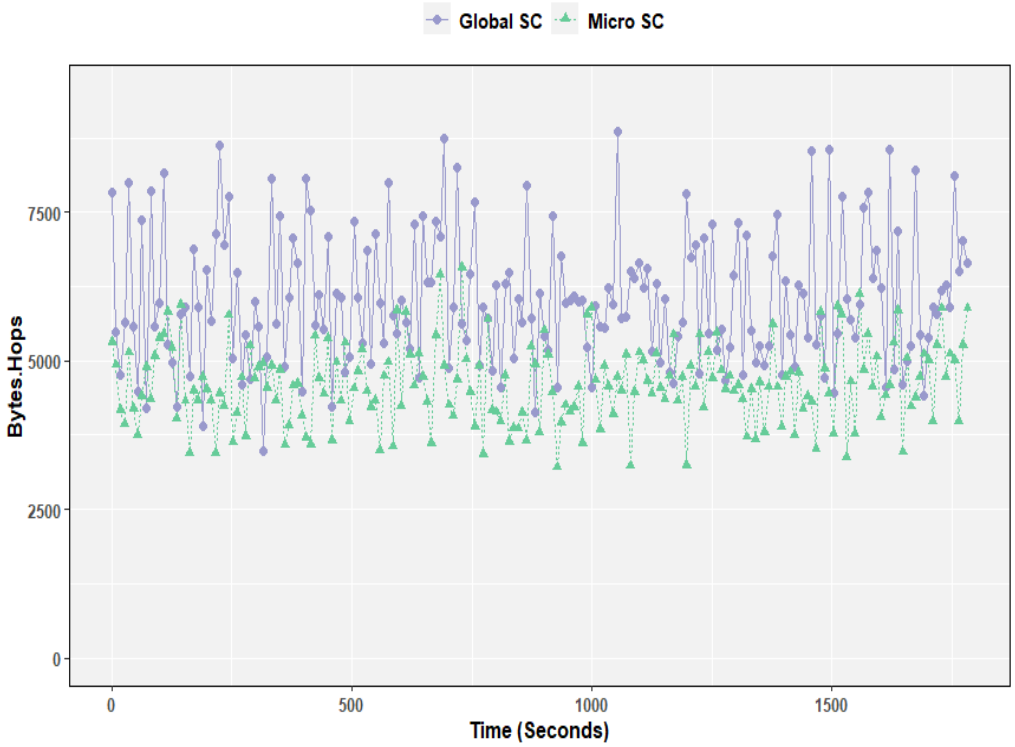

Figure 10. Signalling cost (SC) for IP-over-ICN micro and global mobility support.

5.3. Total Cost Evaluation for Global vs. Micro Mobility Support

Figure 11 shows the total PDC and SC incurred from the simulation scenarios above. We observe from the figure that IP-over-ICN incurs a total PDC of approximately 7.2×10^9 Bytes to support global mobility compared to 5.8×10^9 Bytes to support micro mobility. In terms of SC, IP-over-ICN incurs a total cost of approximately 10.7×10^6 Bytes to support global mobility, compared to 7.9×10^6 for micro mobility. Note that, in this figure, the inset graph is magnified from the main graph to show the scale of SC. It can be seen from the figure that the total SC is only a very small fraction of the total PDC, while it offers flexible and efficient global mobility support within and across network domains, which is a service essentially required by many of the emerging IoT use cases.

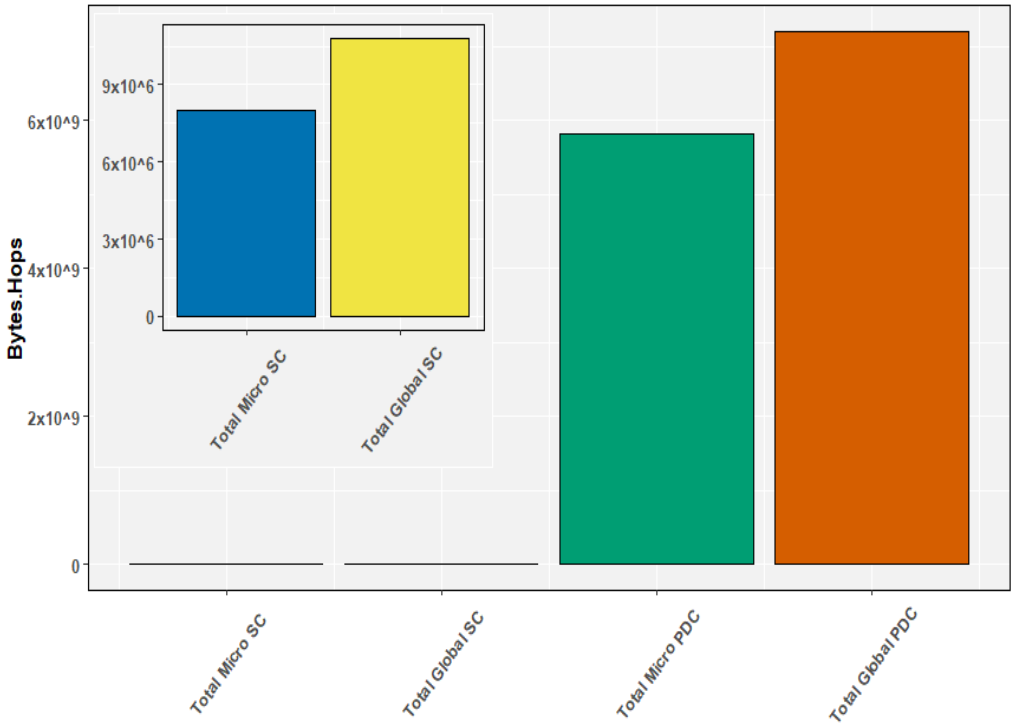

Figure 11. Total signalling cost (SC) and packet delivery cost (PDC) for IP-over-ICN Micro and global mobility support.

6. Conclusions

This paper has presented a global mobility management solution for IoT networks that exploits a path-based forwarding fabric together with mechanisms from Information-Centric Networking. The solution offers micro (intra-domain) and macro (inter-domain) mobility services with a path-based forwarding infrastructure at its heart. The solution offers the flexibility required in many IoT scenarios to support a range of different protocols at the edge such as HTTP, CoAP, TCP or IPv4/v6, while the NAP serves as an entry gateway point to the ICN network and maps the chosen protocol abstraction to ICN. The solution also addresses the fact that most IoT applications and use cases today are no longer centred around end host connectivity but rather around the information content available. Therefore, emerging mobile Information-Centric IoT use cases (specifically IoT sensory applications) such as healthcare, marine cartography, habitat conservation, climate change, etc, can be supported more efficiently.

Author Contributions: Conceptualization, M.A.-K.; methodology, M.A.-K. and M.I.B.; software, M.A.-K.; validation, M.A.-K. and H.M.P.; formal analysis, M.A.-K. and R.A.-Z.; investigation, M.A.-K. and R.A.-Z.; resources, M.A.-K. and A.M.A.; data curation, R.A.-Z.; writing—original draft preparation, M.A.-K.; writing—review and editing, M.A.-K., A.M.A., H.M.P. and M.I.B.; visualization, R.A.-Z.; supervision, M.H.; project administration, M.H.; funding acquisition, M.A.-K. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Passarella, A. A survey on content-centric technologies for the current Internet: CDN and P2P solutions. *Comput. Commun.* **2012**, *35*, 1–32. [CrossRef]
2. Anandhan, A.; Shuib, L.; Ismail, M.A.; Mujtaba, G. Social Media Recommender Systems: Review and Open Research Issues. *IEEE Access* **2018**, *6*, 15608–15628. [CrossRef]
3. Cisco Visual Networking Index: Forecast and Trends. 2021. Available online: https://www.cisco.com/c/en/us/solutions/collateral/service-provider/visual-networking-index-vni/white-paper-c11-741490.html (accessed on 5 February 2022).
4. Premsankar, G.; Di Francesco, M.; Taleb, T. Edge computing for the Internet of Things: A case study. *IEEE Internet Things J.* **2018**, *5*, 1275–1284. [CrossRef]
5. Lee, J.H.; Ernst, T.; Chung, T.M. Cost analysis of IP mobility management protocols for consumer mobile devices. *Consum. Electron. IEEE Trans.* **2010**, *56*, 1010–1017. [CrossRef]
6. Ahlgren, B.; Aranda, P.A.; Chemouil, P.; Oueslati, S.; Correia, L.M.; Karl, H.; Sollner, M.; Welin, A. Content, connectivity, and cloud: Ingredients for the network of the future. *IEEE Commun. Mag.* **2011**, *49*, 62–70. [CrossRef]
7. Choi, J.; Han, J.; Cho, E.; Kwon, T.; Choi, Y. A survey on content-oriented networking for efficient content delivery. *IEEE Commun. Mag.* **2011**, *49*, 121–127. [CrossRef]
8. Vixie, P. What DNS is not. *Commun. ACM* **2009**, *52*, 43–47. [CrossRef]
9. Diot, C.; Levine, B.N.; Lyles, B.; Kassem, H.; Balensiefen, D. Deployment issues for the IP multicast service and architecture. *Netw. IEEE* **2000**, *14*, 78–88. [CrossRef]
10. Perkins, C. *IP Mobility Support for IPv4*; Technical Report, Internet Engineering Task Force, RFC 3344; 2002. Available online: https://www.rfc-editor.org/rfc/rfc3344 (accessed on 29 June 2022).
11. Wakikawa, R.; Gundavelli, S. *IPv4 Support for Proxy Mobile IPv6*; Technical Report, Internet Engineering Task Force, RFC 5844; 2010. Available online: https://www.rfc-editor.org/rfc/rfc5844 (accessed on 29 June 2022).
12. Johnson, D.; Perkins, C.; Arkko, J. *Mobility Support in IPv6*; Technical Report, Internet Engineering Task Force, RFC 3775; 2004. Available online: https://www.rfc-editor.org/rfc/rfc3775 (accessed on 29 June 2022).
13. Al-Khalidi, M.; Thomos, N.; Reed, M.J.; Al-Naday, M.F.; Trossen, D. Anchor free IP mobility. *IEEE Trans. Mob. Comput.* **2018**, *18*, 56–69. [CrossRef]
14. Jokela, P.; Zahemszky, A.; Esteve Rothenberg, C.; Arianfar, S.; Nikander, P. LIPSIN: Line speed publish/subscribe inter-networking. *ACM SIGCOMM Comput. Commun. Rev.* **2009**, *39*, 195–206. [CrossRef]
15. Reed, M.J.; Al-Naday, M.; Thomos, N.; Trossen, D.; Petropoulos, G.; Spirou, S. Stateless multicast switching in software defined networks. In Proceedings of the IEEE International Conference on Communications (ICC), ICC'16, Kuala Lumpur, Malaysia, 23–27 May 2016.
16. Shepherd, G.; Dolganow, A. Bit Indexed Explicit Replication (BIER) Problem Statement. Internet-Draft draft-ietf-bier-problem-statement-00. 2016. Available online: https://www.ietf.org/archive/id/draft-ietf-bier-problem-statement-00.txt (accessed on 23 July 2022).
17. Gundavelli, S.; Leung, K.; Devarapalli, V.; Chowdhury, K.; Patil, B. *Proxy Mobile IPv6*; Technical Report, Internet Engineering Task Force, RFC 5213; August 2008. Available online: https://datatracker.ietf.org/doc/rfc5213/ (accessed on 29 June 2022).
18. Modares, H.; Moravejosharieh, A.; Lloret, J.; Salleh, R.B. A survey on Proxy Mobile IPv6 handover. *IEEE Syst. J.* **2016**, *10*, 208–217. [CrossRef]
19. Ali-Ahmad, H.; Ouzzif, M.; Bertin, P.; Lagrange, X. Comparative performance analysis on dynamic mobility anchoring and proxy mobile IPv6. In Proceedings of the 2012 15th International Symposium on IEEE Wireless Personal Multimedia Communications (WPMC), Taipei, Taiwan, 24–27 September 2012; pp. 653–657.
20. Lee, J.H.; Bonnin, J.M.; You, I.; Chung, T.M. Comparative Handover Performance Analysis of IPv6 Mobility Management Protocols. *IEEE Trans. Ind. Electron.* **2013**, *60*, 1077–1088.
21. Giust, F.; Bernardos, C.J.; De La Oliva, A. Analytic Evaluation and Experimental Validation of a Network-Based IPv6 Distributed Mobility Management Solution. *IEEE Trans. Mob. Comput.* **2014**, *13*, 2484–2497. [CrossRef]
22. Kim, M.S.; Lee, S.; Cypher, D.; Golmie, N. Performance analysis of fast handover for Proxy Mobile IPv6. *Inf. Sci.* **2013**, *219*, 208–224. [CrossRef]
23. Yokota, H.; Chowdhury, K.; Koodli, R.; Patil, B.; Xia, F. *Fast Handovers for Proxy Mobile IPv6*; Technical Report, Internet Engineering Task Force, RFC 5949; 2010. Available online: https://www.rfc-editor.org/rfc/rfc5949.html (accessed on 29 June 2022).
24. Lucent, A. *The LTE Network Architecture: A Comprehensive Tutorial*; Strategic Whitepaper, Alcatel Lucent; Scientifc Research Publishing: Irvine, CA, USA, 2009.
25. Shetty, R.S. 5G Overview. In *5G Mobile Core Network*; Springer: Berlin/Heidelberg, Germany, 2021; pp. 1–67.
26. Shayea, I.; Ergen, M.; Azmi, M.H.; Çolak, S.A.; Nordin, R.; Daradkeh, Y.I. Key Challenges, Drivers and Solutions for Mobility Management in 5G Networks: A Survey. *IEEE Access* **2020**, *8*, 172534–172552. [CrossRef]
27. Shahrul, M.; Leau, Y.B.; Yan, Z.; Anbar, M. Hierarchical Naming Scheme In Named Data Networking for Internet of Things: A Review and Future Security Challenges. *IEEE Access* **2022**, *10*, 19958–19970.
28. Nasir, N.A.; Jeong, S.H. Fast Content Delivery Using a Testbed-Based Information-Centric Network. *IEEE Access* **2021**, *9*, 101600–101613. [CrossRef]

29. Xylomenos, G.; Vasilakos, X.; Tsilopoulos, C.; Siris, V.A.; Polyzos, G.C. Caching and mobility support in a publish-subscribe internet architecture. *IEEE Commun. Mag.* **2012**, *50*, 52–58. [CrossRef]
30. PURSUIT Project. Available online: https://www.fp7-pursuit.eu/ (accessed on 29 July 2020).
31. Lee, J.; Cho, S.; Kim, D. Device mobility management in content-centric networking. *IEEE Commun. Mag.* **2012**, *50*, 28–34. [CrossRef]
32. Augé, J.; Carofiglio, G.; Grassi, G.; Muscariello, L.; Pau, G.; Zeng, X. MAP-Me: Managing anchor-less producer mobility in content-centric networks. *IEEE Trans. Netw. Serv. Manag.* **2018**, *15*, 596–610. [CrossRef]
33. Augé, J.; Carofiglio, G.; Grassi, G.; Muscariello, L.; Pau, G.; Zeng, X. Anchor-less producer mobility in ICN. In Proceedings of the 2nd ACM Conference on Information-Centric Networking, San Francisco, CA, USA, 30 September–2 October 2015; pp. 189–190.
34. Azgin, A.; Ravindran, R.; Chakraborti, A.; Wang, G.Q. Seamless producer mobility as a service in information centric networks. In Proceedings of the 3rd ACM Conference on Information-Centric Networking, Kyoto, Japan, 26–28 September 2016; pp. 243–248.
35. Huang, H.; Rui, L.; Zheng, W.; Niu, D.; Qiu, X. CMLP: Exploiting caches at multiple levels of proxies to enhance seamless mobility support in information-centric networks. *China Commun.* **2016**, *13*, 86–107. [CrossRef]
36. Adhatarao, S.; Arumaithurai, M.; Kutscher, D.; Fu, X. NeMoI: Network mobility in ICN. In Proceedings of the 2018 10th International Conference on IEEE Communication Systems & Networks (COMSNETS), Bengaluru, India, 3–7 January 2018; pp. 251–258.
37. Chandrasekaran, G.; Wang, N.; Hassanpour, M.; Xu, M.; Tafazolli, R. Mobility as a service (MAAS): A D2D-based information centric network architecture for edge-controlled content distribution. *IEEE Access* **2018**, *6*, 2110–2129. [CrossRef]
38. Musa, S.S.; Zennaro, M.; Libsie, M.; Pietrosemoli, E. Mobility-aware proactive edge caching optimization scheme in information-centric iov networks. *Sensors* **2022**, *22*, 1387. [CrossRef] [PubMed]
39. Hou, R.; Zhou, S.; Cui, M.; Zhou, L.; Zeng, D.; Luo, J.; Ma, M. Data forwarding scheme for vehicle tracking in named data networking. *IEEE Trans. Veh. Technol.* **2021**, *70*, 6684–6695. [CrossRef]
40. Wu, F.; Yang, W.; Lu, J.; Lyu, F.; Ren, J.; Zhang, Y. RLSS: A Reinforcement Learning Scheme for HD Map Data Source Selection in Vehicular NDN. *IEEE Internet Things J.* **2022**, *9*, 10777–10791. [CrossRef]
41. Shannigrahi, S.; Fan, C.; White, G. Bridging the ICN Deployment Gap with IPoC: An IP-over-ICN protocol for 5G Networks. In Proceedings of the 2018 Workshop on Networking for Emerging Applications and Technologies, Budapest, Hungary, 20 August 2018; ACM: New York, NY, USA, 2018; pp. 1–7.
42. Moiseenko, I.; Oran, D. TCP/ICN: Carrying TCP over content centric and named data networks. In Proceedings of the 3rd ACM Conference on Information-Centric Networking, Kyoto, Japan, 26–28 September 2016; pp. 112–121.
43. Xia, Z.; Zhang, Y.; Fang, B. Exploiting Knowledge for Better Mobility Support in the Future Internet. *Mob. Netw. Appl.* **2022**, *27*, 1–17. [CrossRef]
44. Dasgupta, I.; Shannigrahi, S.; Zink, M. A Hybrid NDN-IP Architecture for Live Video Streaming: From Host-Based to Content-Based Delivery to Improve QoE. *Int. J. Semant. Comput.* **2022**, *16*, 1–25. [CrossRef]
45. Trossen, D.; Parisis, G. Designing and realizing an information-centric internet. *IEEE Commun. Mag.* **2012**, *50*, 60–67. [CrossRef]