CI-PMIPv6: An Approach for Inter-domain Network-based Mobility Management

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***Abstract*—This paper presents the Clustered Inter-domain Proxy Mobile Internet Protovol version 6 (CI-PMIPv6), an intra-domain and inter-domain Distributed Mobility Management solution for PMIPv6-based networks. It anticipates the exchange of mobile node information for future handovers using a Distributed Hash Table (DHT) structure. The main advantages of CI-PMIPv6 are: to avoid the introduction of a single point of failure; to allow a fast spread of information among network entities; to take advantage of the execution of inter-domain handover-related operations in parallel with the execution of intra-domain handover-related operations; and to avoid generating bottlenecks. Results show that, in the scenario studied, CI-PMIPv6 handover costs less and suffers less latency and packet loss in comparison with other schemes studied. Additionally, the values of goodput in CI-PMIPv6 are greater.**

Keywords*–*CI-PMIPv6; Distributed; Handover; Inter-domain.

I. Introduction

The evolution and widespread use of multimedia applications for mobile gadgets are the key factors for the rapid growth in the use of mobile networks. Mobile data traffic grew 60% between Q1 2015 and Q1 2016 [1]. Additionally, the emergence of mobile devices connected to vehicles expand the possibilities for use-case scenarios. Thus, efficient solutions for mobility management are a relevant and contemporary concern. Binding updates and tunneling setup are the main operations in IP mobility management and, therefore, the applicability of the related protocol may well be determined by how efficient these are. The Internet Engineering Task Force (IETF) Networking Working Group proposed the Proxy Mobile IPv6 (PMIPv6) protocol [2] mainly to resolve issues related to the energy saving and high latency found in Mobile IP (MIP). PMIPv6 introduces two types of entities: the Mobile Access Gateway (MAG), which tracks the location of the current Mobile Node (MN); and the Local Mobility Anchor (LMA), which plays a similar role as the MIP's Home Agent in a local domain. Signaling between MAG and LMA is responsible for updating the binding of the MN. Due to relying on a non-mobile entity to keep track of the MN, PMIPv6 has lost the MIPv6 inter-domain feature. Studies have been proposed on PMIPv6-based inter-domain solutions. However, they still face problems related to centered entities and the high cost of signaling.

In this paper, we propose CI-PMIPv6, a low cost and a low latency intra-domain and inter-domain solution. CI-PMIPv6 makes inter-domain handover possible by spreading information on MNs efficiently among LMAs from the different domains. Intra-domain handover is minimally changed to send useful updates for future inter-domain handovers to those LMAs. The main characteristics of CI-PMIPv6 are:

- **Distributed mobility management** - LMAs from each domain form a cluster, which runs a Kademlia-based DHT [3] so as to spread information efficiently; this avoids the use of global entities and, thus, avoids creating single points of failure and performance bottlenecks;
- **Network-based handover** - CI-PMIPv6 maintains the PMIPv6 advantage of reducing MNs' consumption of energy by avoiding host-based handover signaling and processing overheads;
- **Reuse of existing PMIPv6 entities to exchange inter-domain information** - the compatibility with PMIPv6 legacy systems is achieved; additionally, MAGs may remain unaware of inter-domain mobility, as in PMIPv6;
- **Anticipation of MN information for future handovers** - during the MN's ongoing handover, its current LMA proactively spreads the MN information to neighbor LMAs in the cluster; this information is needed for future inter-domain handovers and is rapidly available to neighbors LMAs, thereby avoiding time waste during such handovers due to the extra signaling needed to request and obtain such information.

By using CI-PMIPv6 it is expected that low inter-domain handover cost and latency will be achieved in comparison with other PMIPv6-based inter-domain approaches cited in the literature. The remainder of this paper is organized as follows: CI-PMIPv6 is detailed in Section II. Related work is presented in Section III. Section IV deals with evaluating the performance of CI-PMIPv6 and the results achieved. Finally, some conclusions are drawn and suggestions made for future research studies in Section V.

II. CI-PMIPv6

Figure 1 presents the CI-PMIPv6 architecture and shows that the LMAs form a cluster. Each LMA contains a Kademlia peer [3], and they are all connected to the same DHT. The choice of a Kademlia-based Peer to Peer (P2P) architecture for the cluster allows:

- LMAs to communicate without placing them in a hierarchy;
- Mobility management without centralized entities, thus avoiding bottlenecks and a single point of failure;

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- MAGs to abstract the existence of the cluster, which is recognized only by the LMAs, thereby avoiding unnecessary signaling between the local domain and the core network;
- The MN information to be spread efficiently throughout the Kademlia `STORE` primitive.

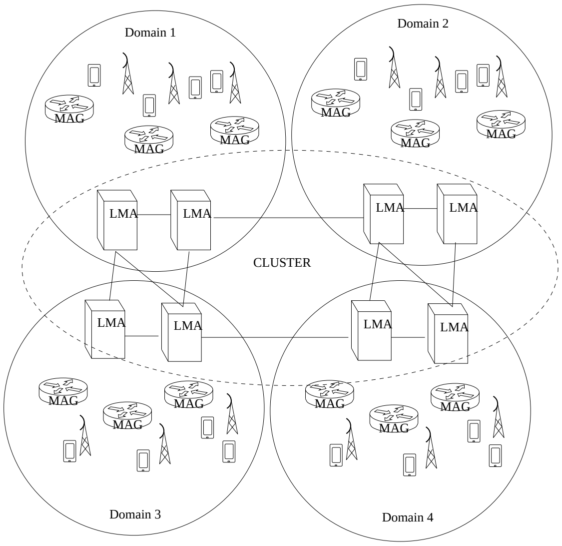

Figure 1. Domains in CI-PMIPv6.

The MN information is stored in its original LMA, which forwards it to its neighbors. Each piece of information in the cluster is represented in a <key, value> pair format, where:

- The key is the MN original IP address;
- The value is a triple of <MN current IP, MAG IP, LMA IP>.

The <key, value> pairs are stored in peers whose nodeIDs are the closest to the key. The nodeID, i.e., the identifier of the LMA as a Kademlia peer, is the LMA IP Address. Both keys and nodeIDs are in the 128-bit space, as in every IPv6 address, instead of in the 160-bit space as in the standard Kademlia proposal [3].

The `PING`, `STORE`, `FIND_NODE`, `FIND_VALUE` primitives, and the look-up procedures from Kademlia are valid for network refresh, information storage, location of peers, and information retrieval in the cluster. Selecting and registering LMAs in the same DHT is done according to agreements among engaged network operators. Likewise, CI-PMIPV6 introduces the new primitives `UPDATE` and `DELETE`. They are responsible for refreshing and removing <key, value> pairs in the cluster. These primitives follow the same logic as in the `STORE` primitive.

Figure 2 shows the signaling call flow for intra-domain handover. The flow is similar to that proposed by the PMIPv6 standard. After triggering the layer-2 event, the previous MAG (PMAG) exchanges deregistration signaling with the LMA. The LMA waits for a fixed interval before removing the binding definitively. When visiting the new network, the MN requests the new MAG (NMAG) for a route via the Internet Control Message Protocol (ICMP) `Rtr Sol.` message. Then, the NMAG must request the LMA to update its binding table with the messages *Proxy Binding Update* (PBU) and *Proxy Binding Acknowledgment* (PBA). A tunnel is set up between the LMA and NMAG to forward packets to the MN. The NMAG, then, may send the ICMP `Rtr Adv.` message to announce itself as the access router for that MN and then, the handover is finished. CI-PMIPv6 adds to that flow a call to the cluster `UPDATE` message. Thus, whenever the MN associates itself with a MAG, the cluster is updated. We assume that the LMA runs both the update operation and the rest of the intra-domain handover operation in parallel, e.g., the LMA runs both of the operations simultaneously on different cores. These two operations do not block each other. This is possible since the spread of binding information in the cluster is not useful for concluding the current intra-domain handover. MAGs do not need to interact with the cluster and may proceed with the handover normally. We further assume to be negligible the amount of time spent performing a system call for starting the update operation during intra-domain handovers. We also assume that traffic from the LMA to the cluster and traffic from the LMA to the MAGs can be kept isolated from each other. For instance, each LMA might have exclusive network interfaces and paths for communicating with MAGs. In this manner, update messages flowing from the LMA to the cluster during intra-domain handovers cannot block (e.g., head-of-the-line blocking in network interfaces) or affect (e.g., increasing queuing delay) messages flowing to the MAGs. The MN information is proactively spread in the cluster. The information will be necessary if there is ever an inter-domain handover executed by the MN. The MN information is rapidly available to neighbors LMAs in the cluster, thereby avoiding the need for the extra signaling to request and obtain such information during inter-domain handovers. Notice that CI-PMIPv6 takes advantage of the execution of inter-domain handover-related operations in parallel with the execution of intra-domain handover-related operations.

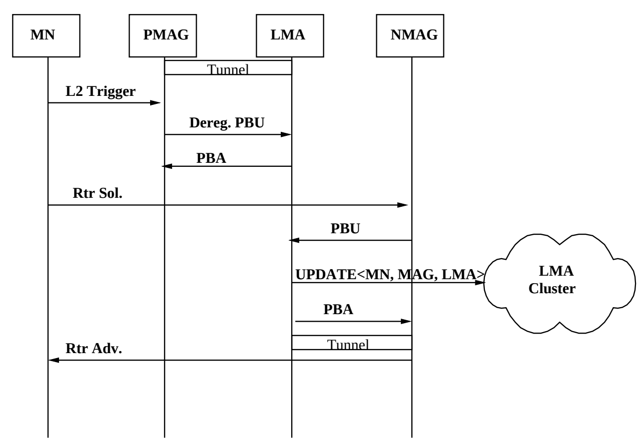

Figure 2. Intra-domain handover in CI-PMIPv6.

Figure 3 shows the signaling call flow for an inter-domain handover. The procedure is initially similar to the intra-domain handover. When detecting the link layer trigger, the PMAG sends the `Dereg.PBU` message to the previous LMA (PLMA). The PLMA sets a timer to wait for a period of time before removing the binding information in order to prevent a ping-pong effect. The MN enters the new domain and asks NMAG for a new route. The NMAG sends a `PBUNoProf` message to the LMA in its domain (new LMA - NLMA) to inform it that the MN was not originally registered in that domain. The NLMA searches for the MN IP in its cluster history and finds out that it originally belongs to the PLMA domain. Then, NLMA responds to NMAG with a `PBAProf` message containing the node information needed for registration. After that, the NLMA sends a `PBUInterdomain` message to the PLMA informing that the MN has entered a new domain. Thus, PLMA refrains from removing the node binding. This must happen before the timeout set aside for the removal in the PLMA. It updates its own cluster history instead and sends an `UPDATE` message to the cluster. In parallel, PLMA sends the `PBAInterdomain` message to the NLMA informing it that it is ready to redirect data traffic to the NMAG in the new domain. Thus, a tunnel is set up between PLMA and NMAG. It is important to notice that PLMA remains the anchor entity for the MN until the session ends. This simplifies the process of context switching.

The greatest CI-PMIPv6 opportunity for performance gains comes from the anticipated knowledge that LMAs get from cluster updates. The information obtained is useful in future inter-domain handovers. CI-PMIPv6 avoids the MAG, which is a local domain entity, to exchange handover signaling with the core network, where the cluster is and also where the network traffic is more intense. Additionally, the fact that the PLMA still manages communication after the inter-domain handover eliminates the need to create an additional tunnel, a tunnel between two LMAs. This avoids increasing the overhead of tunneling.

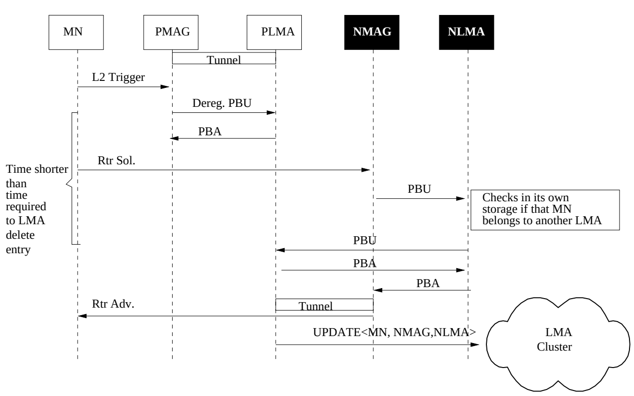

Figure 3. Inter-domain handover in CI-PMIPv6.

III. Related Work

Park *et al.* [4] present a scheme where the LMA from a domain forwards the handover signaling to the LMA in another domain to achieve inter-domain handover. There are neither optimizations, nor additional entities. The consequence is the introduction of an extra tunnel between those LMAs and a duplicated number of signaling messages. Simulations with QualNET measures packet loss and latency in comparison with a scheme with PMIPv6/MIPv6 interworking. The authors state that the proposal is better suited for scenarios where handover is frequent. A similar proposal can be found in [5].

Zhong *et al.* propose the Enabling Inter PMIPv6 Domain Handover (EIPMH) [6]. The authors introduce the Traffic Distributor (TD), an entity that redirects data to the LMA while the MN is out of the original domain. The TDs are statically configured and have knowledge about other TDs, their IP prefixes, and mapping to the LMAs. In that proposal, the TD is responsible for assigning prefixes to its MNs instead of the LMA. The NLMA must send a query `PBU_Forwading` to the PLMA to find additional information about the MN and the TD responsible for communicating with the Internet. The TD also creates a tunnel to the NLMA. Also, there are tunnels between LMAs and between the NLMA and the MAG. The NS-2 simulation tool is used to evaluate performance. Latency and throughput are compared to those found in I-PMIP. However, the evaluation does not consider the extra overhead derived from the tunnel between the TD and the NLMA. The process of finding the PLMA, look-up for the NLMA, and the change of MAGs are not considered.

In the Newman *et al.* proposal [7], the original LMA keeps managing the node until the end of the session and exchanges signaling with the MAG in the new domain during inter-domain handover. That LMA is called the Session Mobility Anchor (SMA). It is assumed that LMAs from different domains already know each other and are physically close to each other. To locate the MAG in the new domain, the original LMA relies on a centralized entity called the Virtual Mobility Anchor (VMA), which undertakes location updates whenever a handover takes place. Hence, that solution faces the same single point of failure issue as in [6]. The authors state that I-PMIP sees to it that the policies of different domains remain transparent, since there is no direct connection between MAGs from different domains. Performance is evaluated by a theoretical analysis, which compares the I-PMIP latency to the latency found in MIP, and Hierarchical approaches for MIP and PMIP. According to [7], I-PMIP has proven to be more efficient in the scenarios studied. Nyguyen and Bonnet propose a similar solution in [8] focusing on routing optimizations.

Joe *et al.* [9] present an inter-domain approach based on an architecture that considers special types of MAG: the Boundary and Overlapping MAG (BMAG and OMAG, respectively). The BMAG is associated with only one LMA, while the OMAG is associated with more than one domain. Both are found in regions where a domain ends and another domain begins. Also, only one authentication entity for all domains is considered. The presence of a gateway guarantees maintenance of the IP address. The authors propose two solutions: Reactive and No-Gap. In the Reactive solution, a path is created between CN and PLMA and NLMA. The BMAG discovers a NLMA by geographical locating it. The authors do not specify how the look-up is done. The functionality of the BMAG is shared with edge routers. A tunnel must be created between the gateway and the NLMA, between LMAs, and between the PLMA and the NMAG. In the No-Gap approach, the OMAG has information from both domains and creates two simultaneous paths as the MN enters its area. Thus, the MN receives redundant information from both LMAs. Besides the PMIPv6 messages, extra signaling is exchanged between the NLMA and the gateway to confirm and obtain additional information about the MN. Additionally, the NLMA must authenticate the MN. A tunnel must be created between the gateway and the NLMA, and between the NLMA and the OMAG. The performance evaluation compares the solution with MIPv6, Fast Handovers for MIPv6, I.PMIPv6, and EIPMH by measuring handover latency. What may well be noticed is that the Reactive mode

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TABLE I. CI-PMIPV6 AND RELATED WORK COMPARISON.

Solution	# extra messages in interdom. HO	# extra tunnels	Infrastructure maintenance	Compatibility with legacy systems
No-opt [4]	8	1	Yes	Yes
EIPMH [6]	6	2	No	No
I-PMIP [7]	6	1	No	No
No-Gap [9]	4	1	No	Yes
CI-PMIPv6	4	0	Yes	Yes

leads to greater overheads because of an additional tunnel in comparison to the No-Gap model. According to the authors, the No-Gap model is the most efficient model. This is why this paper gives more focus to the No-Gap solution, which has a counterpart in [10].

Table I summarizes the differences between CI-PMIPv6 and other inter-domain solutions. The non-optimized approach [4] has the greatest increase in extra signaling in comparison with the original implementation of PMIPv6. Additionally, there might be an overhead related to the addition of one more IP header caused by the extra tunnel. These factors may be responsible for a remarkable increase in latency during the inter-domain handover. The advantage is the absence of new entities and the compatibility with the PMIPv6 legacy system.

The EIPMH [6] introduces the TD - a centralized entity - to manage the transition between two LMAs. The authors acknowledge that there may be more than one distributor, each of which is responsible for a coverage area. Nevertheless, the handover between distributors is not covered by the authors. Furthermore, the solution adds two extra tunnels and requires changes in the infrastructure of the network.

I-PMIP [7] requires the existence of a centralized entity to maintain MNs information. It creates a single point of failure and causes changes in the network infrastructure. Additionally, the extra tunnel added may increase the packet delivery overhead.

The No-Gap solution [9] is one of the least expensive solutions in terms of signaling overhead. However, it requires changes in legacy border routers and generates redundant data packets in the same MAG, coming from different LMAs.

CI-PMIPv6 appears to be the least expensive solution, since the extra signaling necessary for inter-domain handover is one of the lowest, when compared with other solutions. It does not require extra tunnels and may interwork with PMIPv6 legacy systems. The cluster messages do not add extra signaling costs to the ongoing handover, since they are asynchronous and are necessary only in future inter-domain handovers. Thus, we expect that CI-PMIPv6 will have a smaller handover cost, lower latency - as a consequence, less packet loss - and a higher useful traffic rate than the other proposals.

IV. PERFORMANCE EVALUATION AND RESULTS

In this section, CI-PMIPv6 performance is compared to non-optimized, No-Gap, I-PMIP, and EIPMH solutions. The evaluation is based on the analytical modeling presented in [11] [12] [13]. This allows the cost of handover signaling in a session, latency and the packet loss of one handover, and the goodput in a session to be measured. We consider that mobile devices are attached to vehicles in a highway during a voice call (e.g., Skype). Inter-domain handover takes place as the MN arrives at a new domain. The mobility pattern follows the Fluid-Flow model [14]. That model considers average velocity (v), the subnet and domain coverage areas (A_M and A_D, respectively) and the subnet and domain perimeters (L_M and L_D, respectively) as parameters. The direction of movement is uniformly distributed in a range of 0 to 2π. Since this experiment is interested in a vehicular scenario, the choice of this model is very appropriate.

Two variables determine the dynamics of the MN: the domain crossing rate (μ_D) and the subnet crossing rate (μ_M). The former is the rate at which the node switches from one domain to another. It is equivalent to the inter-domain handover rate (Ng). The latter is the rate at which the node switches from one subnet to another. The intra-domain handover rate (Nl) considers a subnet crossing when this does not imply a domain crossing. That is, Nl is the difference between μ_M and μ_D. Their equations are as follows [11] [13]:

$$\mu_M = \frac{vL_M}{\pi A_M}, \tag{1}$$

$$Ng = \mu_D = \frac{vL_D}{\pi A_D}, \tag{2}$$

$$Nl = \mu_M - \mu_D. \tag{3}$$

Another important parameter to describe mobility of a node is the Session-to-Mobility Ratio (SMR), which relates session arrival rate and the subnet crossing rate as follows [11]:

$$SMR = \frac{\lambda_S}{\mu_M}. \tag{4}$$

If SMR is near zero, this means that the node has high mobility. The higher the SMR, the more static the node.

The signaling cost is the number of handover signaling messages, taking into consideration the distance in hops between two entities x and y, namely $H_{(x-y)}$, the underlying media, and the processing cost. For each protocol message sent, the signaling cost is (see [11])

$$C_{x-y} = \alpha(H_{(x-y)}) - \beta + PC_y, \tag{5}$$
$$PC_y = \varsigma \log N^y_{MN}, \tag{6}$$

where the parameters α and β represent the coefficients of unity transmission costs (in messages/hop) in wired and wireless links, respectively. The cost of processing at one end is represented by PC_y. It is measured based on a logarithmic search in a data structure with the size of the number of MN entries and a normalizing constant ς equivalent to the bandwidth allocation. If the reception of a message at one end does not imply the search in a local storage, PC_y is considered zero. Additionally, if the node that sends or receives the message is not an MN, the β factor is excluded. The handover signaling cost is the sum of the cost of all messages exchanged during a handover. The average cost is measured as a weighted sum of the intra-domain and inter-domain counterparts. It depends on Ng and Nl rates. The average cost [11] is presented as

$$cost = \frac{intraDHO\ cost \times Nl + interDHO\ cost \times Ng}{Nl + Ng}. \quad (7)$$

The inter-domain signaling cost for a session is the cost of one inter-domain handover multiplied by both Ng and the session duration:

$$cost\ in\ session = interDHO\ cost \times Ng \times session\ duration. \quad (8)$$

Handover latency is measured as the handover duration, i.e., the time a node spends without effective communication. The latency equation for a message exchanged between two nodes *x* and *y* is (see [13])

$$T_{x-y} = \frac{1+q}{1-q}\left(\frac{M_{size}}{B_{wl}} + L_{wl}\right) + H_{x-y}\left(\frac{M_{size}}{B_w} + L_w + T_q\right). \quad (9)$$

The first part of the sum is the wireless overhead and it must be excluded if neither *x* nor *y* is a wireless device. The second part is the overhead in the wired medium. The parameter q is the probability of failure of the wireless link, M_{size} is the average length of a message, and B_{wl} and B_w are the wireless and wired bandwidths, respectively. The propagation delay in wireless and wired media are L_{wl} and L_w, respectively. The average queuing delay in each router is represented by T_q. Handover latency is the sum of the latency of all signaling messages exchanged during a handover. As in the signaling cost, the average latency is measured as a weighted sum of the intra-domain and inter-domain counterparts as follows [11]:

$$latency = \frac{intraDHO\ lat \times Nl + interDHO\ lat \times Ng}{Nl + Ng}. \quad (10)$$

The average packet loss in a handover is the average number of packages not sent/received during handover. The packet loss (PL) is the product of the handover latency and the packet arrival rate (λ_p) [11], i.e.,

$$PL = T\lambda_p. \quad (11)$$

Finally, the goodput is a measure that relates the useful data traffic during a session and the total traffic (TOT), which is the total number of bytes transmitted during a session. The goodput is determined as follows (cf. [11]):

$$Goodput = \frac{TOT - (P_{size} \times PL_{session} + TOT \times PD)}{session\ duration}, \quad (12)$$

$$TOT = session\ duration \times \lambda_p \times P_{size}, \quad (13)$$

$$PD = \frac{40 \times H_{tunnel}}{(40 + P_{size}) \times H_{MN-CN}}. \quad (14)$$

Goodput additionally depends on the packet loss and the packet delivery (PD) overhead. PD overhead is the cost of tunneling the IP-in-IP extra 40-byte header along the path between an MN and its correspondent node (H_{MN-CN}). Packet size (P_{size}) and the PMIPv6 tunnel size in hops (H_{tunnel}) are parameters for the PD.

TABLE II. EVALUATION PARAMETERS.

Parameter	Default value
Number of subnets per domain	7
Coverage area of each subnet (A_M)	1.87 km^2
Kademlia's constant (k)	10
MN velocity (v)	15 m/s
Prob. of failure of the wireless link (q)	0.5 (range 0-0.8)
Coefficient of cost in wired medium (α)	1 message/hop
Coefficient of cost in wireless medium (β)	10 messages/hop
Normalizing constant (ς)	0.01
Queuing time (T_q)	5 ms
Subnet residency time (1/μ_M)	300 s
Prop. delay (wired link) (L_w)	0.75 μs
Prop. delay (wireless link) (L_{wl})	10 ms
Packet arrival rate (λ_p)	38 packets/s (100 kbps)
Session arrival rate (λ_S)	0.001 sessions/s
Average data packet size (P_{size})	300 bytes
Average signaling packet size (M_{size})	160 bytes

Now, we turn our attention to the perfomance evaluation of CI-PMIPv6. The signaling cost in a session is measured as a funcion of SMR. Latency and packet loss in one handover are measured as a function of the probability of failure of the link in the wireless network. The goodput in a session is measured as a function of SMR.

We consider in our evaluations that a domain has 7 subnets. Each subnet follows a hexagonal model and has one MAG. There is a central subnet that is managed by a single LMA. The other subnets surround the central subnet. The coverage area of each subnet is equal to 1.8 km^2 and the perimeter is equal to 5 km. Table II summarizes the values of the parameters used for performance evaluation. The Kademlia parameter *k* used in CI-PMIPv6, which represents the size of the neighborhood, is set to 10. This value is chosen based on a scenario where nodes have an average speed of 15 m/s (60 km/h) and may cross 10 domains during a session. The probability of failure of the wireless link ranges from 0 to 0.8 in experiments to consider the radio channel under different quality conditions during handover. The greater this probability is, the more link-layer retransmissions are necessary. We consider α to be equal to 1 message/hop and β to be equal to 10 messages/hop, since wireless links tend to cost more than wired links. The average queue time is a typical value of 5 ms. We consider that the average residency time of an MN is equal to 300 s, which corresponds to a mean speed of 15 m/s. The theoretical latency across a 4G LTE interface is in the order of 10 ms. We assume that the wireless link has a propagation delay of 10 ms in order to capture such behaviour. The propagation delay of wired links are assumed to be a typical value for Fast Ethernet. The arrival rate of packets corresponds to a voice call (e.g., Skype) and the session arrival rate allows consecutive voice calls that are 13 minutes long each. We consider that the average data packet size is 300 bytes long [15]. The average packet size used for handover signaling is 160 bytes long.

Figure 4 presents the influence of SMR on the overall cost during a session. If SMR is near zero, there is a high mobility scenario. If SMR is high, this means that the network mobility is low. Therefore, the cost tends to be lower with higher values of SMR for all proposals. When SMR tends to zero, there is a high number of handovers during a session. In this case, the number of messages exchanged during handover plays an important role in the overall cost. The scheme with no optimization has the worst performance and CI-PMIPv6 presents the lowest cost, since it requires fewer messages to accomplish handover. Additionally, the presence of a cluster that exchanges domains information proactively and in parallel with the current binding update simplifies the communication during future inter-domain handovers, which require less interaction between core network entities. The CI-PMIPv6 cost is always the lowest. In particular, it is 20% lower than the cost in No-Gap when the SMR is equal to 0.01.

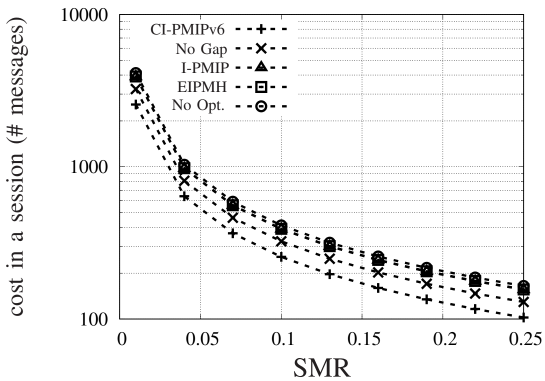

Figure 4. Overall cost *versus* SMR.

Figure 5 presents the average handover latency as a function of the probability of failure of the wireless link. This probability represents the reliability of the wireless channel and may degrade performance due to retransmissions. The EIPMH results are influenced by the high number of interactions in the core network. It has the highest latency until the probability of failure reaches 0.65. From this point on, the scheme without optimization has greater latency. This is due to the fact that it has more messages involving the MN, thus making the scheme more sensitive to the wireless media. I-PMIP presents slightly better results than No Gap. It is important to notice that CI-PMIPv6 presents the smallest results for latency. In particular, CI-PMIPv6 latency is 16% smaller than the latency in I-PMIP when the probability of failure is 0.8. In this case, CI-PMIPv6 still has a handover latency of 410 ms, which is 90 ms lower than the latency in I-PMIP. CI-PMIPv6 performs better because unnecessary interactions in both the core network and the wireless network were eliminated.

Figure 6 presents the number of lost packets as function of the probability of failure of the wireless link. The packet loss is directly related to the handover latency, since no buffering during handover is considered in the protocols. Considering that in this scenario the arrival rate is 38 packets/s, there is a significant loss of quality in the worst case even for the No-Gap scheme, which presents the second best result. The number of lost data packets for CI-PMIPv6 is the smallest in all cases studied. In particular, it is 16% smaller than the value observed for No-Gap when the failure probability is 0.8. The number of lost data packets for CI-PMIPv6 is always the smallest because CI-PMIPv6 has the lowest handover latency.

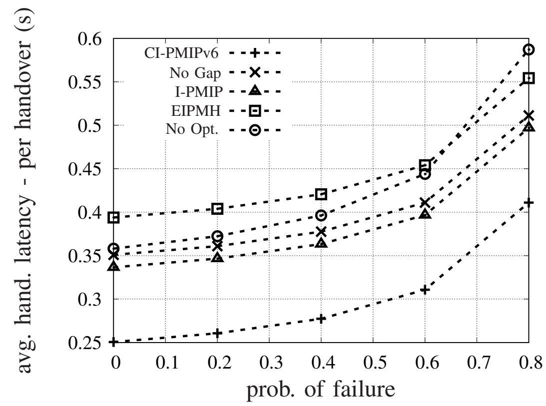

Figure 5. Overall latency *versus* prob. of failure of the wireless link.

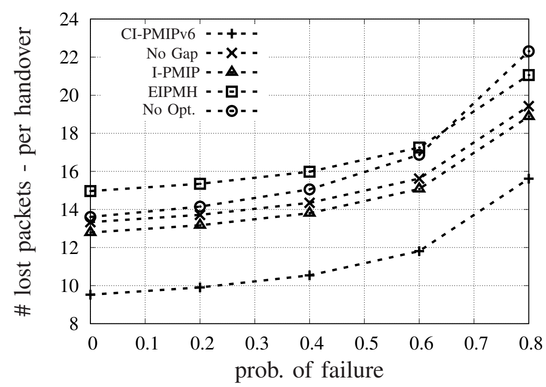

Figure 6. Packet loss *versus* prob. of failure of the wireless link.

Figure 7 presents the goodput *versus* the SMR. If SMR is high, it means that the network mobility is low. Thus, goodput tends to be more stable as SMR grows. CI-PMIPv6 has higher goodput for all SMR values. This means that the proposed scheme can send more useful data during a session. CI-PMIPv6 maintains the same number of tunnels created in PMIPv6. This avoids the PD overhead due to headers in IP-in-IP tunneling. EIPMH has the worst goodput because it requires the creation of two extra tunnels, besides the pre-existing PMIPv6 tunnel.

V. CONCLUSIONS AND FUTURE WORK

This paper presented the CI-PMIPv6 as a distributed solution for inter-domain IP mobility. CI-PMIPv6 has a distributed design, which organizes LMAs from different domains in a cluster as Kademlia peers. In that cluster, information on MNs is spread proactively and in parallel with the current binding update, thereby simplifying future inter-domain handover processes.

CI-PMIPv6 was compared to several inter-domain approaches and results have shown that when CI-PMIPv6 is used, the cost, the latency, and the packet loss in the scenario studied are lower. Additionally, the goodput reaches higher values. In future work, it is intended to extend the solution to FPMIPv6. Further, the application of localized routing techniques may

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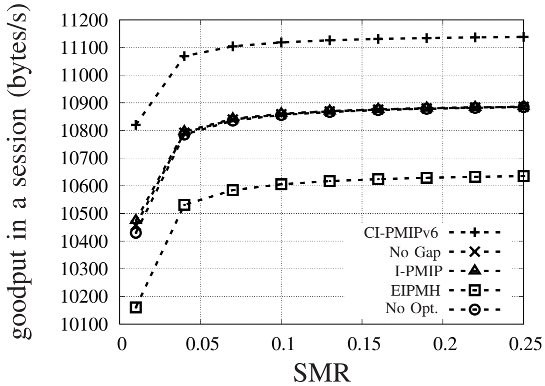

Figure 7. Goodput *versus* SMR.

be applied to optimize the CI-PMIPv6 performance in high mobility scenarios. Simulation experiments with CI-PMIPv6 is further expected. Future experiments with a variable number of domains will highlight the scalability of the cluster in comparison to other architectures.

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