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Performance Evaluation of Mobile Sub-Networks Convergence Approaches in a Personal Distributed Environment

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Abstract: There are two approaches to handle the convergence of mobile sub-networks in the Personal Distributed Environment (PDE). In order to make decision which approach to be used in the PDE, a simulation model was developed to compare the approaches. Based on the simulation model and also analytical studies, performance evaluations were carried out on both approaches. This study will start with the introduction of the PDE concept and followed by the overview of the protocol used to support network mobility in PDE. The explanation of the simulation model and its environment will then follows. This is then followed by the explanation on the implementation of both approaches in the simulation model. The de-convergence of the sub-networks using both approaches will also be discussed. This will then be followed by the discussion on the metrics used to carry out the performance evaluation together with its derivation. The results from the evaluations will then be presented. At the end of this study, the most suitable convergence approach of mobile sub-networks in the PDE will be determined.

Key words: Personal distributed environment, device management entity, mobile sub-network

INTRODUCTION

The mobile virtual center of excellence project has defined the concept of a Personal Distributed Environment (PDE) (Dunlop *et al*., 2003) of a user's devices, services and data. This concept enables a user to access services and data through a distributed set of terminal ubiquitously. An IP-based communication system was proposed to be used by the PDE in order to offer such services to users.

In a single PDE, there will be sub-networks interconnected with one another (Fig. 1). In its architecture, there will be Device Management Entities (DMEs), which will control devices within a single PDE sub-network and also provides universal co-ordination between the sub-networks. More interestingly, in the concept of PDE, some of the sub-networks are also mobile. The scenario of a whole network becomes mobile deserves a special attention and need to be addressed appropriately.

When a user moves away from a fixed Sub-network (e.g., his/her home), a mobile sub-network (in this case a Personal Area Network (PAN)) will be created consisting of whatever devices the user retains. At this point, the sub-network will start to change its point of attachment in the infrastructure. This process must be completed satisfactorily to ensure that the session continuity for all the nodes in the sub-network is maintained.

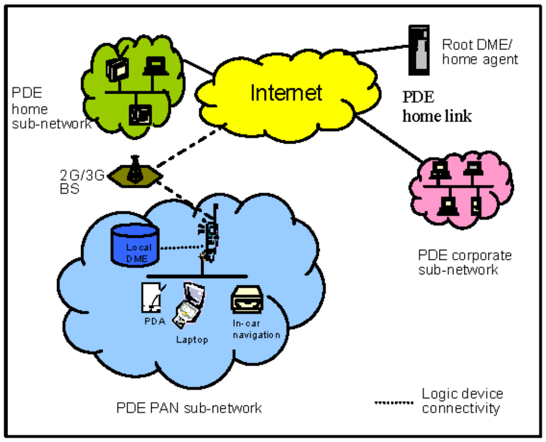

Fig. 1: PDE basic architecture

The scenario outlined could be more complicated if the user and PAN, for example, enters a car and becomes mobile. In PDE, the vehicle itself is considered as a separate sub-network maintaining its own devices, e.g., a global positioning system, car security system and digital radio working in a collaborative way. In effect when the user enters the car, the two sub-networks will merge, which is known as convergence in the PDE. Conversely when the user leaves the car the two networks will separate and this is known as de-convergence in the PDE.

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Network mobility support will enable a network to change its point of attachment in the Internet without involving the nodes inside it. There are a lot of advantages that network mobility can offer, but the most important one is that it would reduce the signalling cost. This is due to the fact that only the node known as the mobile router will perform location update on behalf of the entire mobile network. In addition there is also the issue of convergence of mobile sub-networks in the PDE which also need to be addressed. The need to have network mobility support arises when there is a need to support users who would have access to range of services and data through a distributed set of terminals ubiquitously as offers by personal distributed environment.

In this research, a new protocol to support mobile sub-network mobility has been proposed. PDE-NEMO basic support protocol as it is known or simply PDE-NEMO was developed specially to cater for mobile sub-networks mobility in a PDE. In the PDE-NEMO, there are two approaches proposed to handle mobile sub-networks convergence. This study considers the performance evaluation of mobile sub-networks convergence approaches proposed for the PDE-NEMO.

OVERVIEW OF PDE-NEMO BASIC SUPPORT PROTOCOL

In order to support mobile sub-networks such as the PAN, a protocol known as the PDE-NEMO basic support protocol (PDE-NEMO), has been developed. The protocol is actually an adaptation of the NEMO protocol discussed by Devarapalli *et al.* (2005) and uses the same mobility agents, i.e. the mobile router and the Home Agent as defined by Devarapalli (2005). On top of that, a new mobility agent known as Root DME was introduced.

Compared to NEMO (Devarapalli *et al.*, 2005), the home agent in PDE-NEMO does not advertise the home address of the mobile router to the infrastructure. Instead, the mechanism for other nodes in the infrastructure to locate the device in a PDE is carried out through the usage of SIP Uniform Resource Identifier (URI) as mentioned by Dunlop *et al.* (2003). For this reason also, the home agent in the PDE-NEMO does not have to intercept packets meant for a device in a mobile sub-network. This also helps to reduce signalling traffic in the infrastructure, as the home agent does not have to send gratuitous neighbour advertisement messages.

As with NEMO, the PDE-NEMO protocol also requires a mobile router to have a unique home address through which it is reachable when it is registered with its home agent. Whenever, a mobile sub-network attaches itself to a new point of attachment in the infrastructure, it will request a care-of address from an access router or even a mobile router. After that a Binding Update (BU) message consisting of the new care-of address will be sent to the home agent. Upon receiving the BU message, the home agent will update the appropriate records in the appropriate binding caches. Subsequently, the home agent will send a BU acknowledgment to the mobile router.

Whenever, a correspondent node sends a packet to a device within a mobile sub-network, the packet will be sent to the Root DME first at the PDE home link. The Root DME will find the most appropriate device to receive the packet. After that the root DME will locate the device by contacting the home agent. After the Home Agent finds the current location of the device, the packet will be encapsulated and tunnelled to it. At the other end, upon receiving the encapsulated packet, the mobile router will de-capsulate the packet and then forward it to the intended device.

This study considers the particular situation where the user PAN is required to join another of the user's mobile sub-networks, which will involve the convergence process.

HANDLING THE CONVERGENCE OF MOBILE SUB-NETWORKS IN PDE

The two approaches to handle the convergence of two mobile sub-networks in a PDE are known as the nested approach and the merged approach.

The nested approach: Essentially in this approach a so-called child and parent relationship is created between the two. The Nested mobility concept was also discussed in NEMO (Ernst and Lach, 2007). However, implementation wise, the Nested Approach proposed in this study is different from that explained by Ernst and Lach (2007). The difference lies in the information being exchanged and updated during the nesting process.

According to Devarapalli *et al.* (2005), the home agent maintains a prefix table and also the binding cache information. The prefix table is required for security reasons i.e., to prevent a mobile router from claiming mobile network prefixes belonging to another mobile router. In a PDE, the issue of a mobile router claiming another mobile network's prefixes does not arise. In the proposed PDE-NEMO, the usage of URI can avoid this problem as a mobile router cannot request the home agent to forward a packet belonging to another PDE (a sub-network bearing different URI). The home agent will only forward a packet to a Sub-network bearing the appropriate URI name.

In the PDE-NEMO, a different scheme of data structures is proposed for the home agent. Instead of having a binding cache table and a prefix table, it is proposed to have binding caches for both mobile nodes and mobile routers, leaving out the prefix table i.e. the proposal is to have:

- A binding cache for mobile nodes (to cater for MIPv6) backward compatible)
- A binding cache for mobile routers (to cater for PDE-NEMO)

Both data structures will bind a node with its respective home address. In the case of a mobile node its care-of address would be the home address of the mobile router. This scheme is also compatible with the mobile IPv6 (Johnson and Perkins, 2004). As for the mobile router, its home address would be the IP address that links it to the current sub-network that it is attached to.

The implementation of nested mobility in NEMO (Devarapalli *et al*., 2005) is different. Since, the home agent maintains a prefix table, the nested mobility would be represented by the multi entry of a mobile router with a different prefix each time. The disadvantage of this method is that a new entry has to be created when a mobile router becomes nested to a sub-network. In the implementation, if the nested level is 3, this would mean that there would be 3 entries for the mobile router in the prefix table (each bearing a different prefix i.e. the nested prefix network).

On the contrary, if more than 1 level of nested levels were to be implemented in the PDE-NEMO, the respective mobile routers' care of address in the mobile router binding cache will be pointing to the same care-of address, i.e. the parent mobile router's care-of address. In order to assist the nested approach, two new options in the Dynamic Host Control Protocol (DHCP) protocol are proposed. The time it takes to complete the nesting process is known as nesting time and is represented by T_{Nest}.

The merged approach: In this approach, when two mobile sub-networks converge, they will merge into a single mobile sub-network. A simple rule that had been adopted here is that the incoming mobile sub-network will be disintegrated and its devices would join the other mobile sub-network. Each device in the joining mobile sub-network is involved directly in the merging and de-merging processes and consequently has to execute a location update, informing the home agent of its current location. The time it takes to complete the merging process is known as merging time and is represented by T_{merge}.

EXPERIMENTS

In order to compare the performance of a PDE utilising the Nested or Merged approaches, a simulation model as shown in Fig. 2 has been developed. This model considers the comprehensive signalling exchanges which take place in each case and, in particular, the impact of varying the number of devices in each sub-network. A simplified Gilbert Elliot model (Gilbert, 1960) was used in the simulation model to simulate a more realistic radio channel model. It introduces back to back packet loss in the radio channel. The simplified Gilbert-Elliot model used in the simulation is an approximate characterization of the radio channel. It is sufficient to demonstrate the bursty errors that often faced by radio channel.

Applying the convergence approaches in the simulation model: The simulation model developed is designed to simulate a scenario whereby a user (along with his/her PAN mobile sub-network) has moved out of contact with an Access Router (AR) and has converged with another mobile sub-network and then after some time, de-converges again. In this research, only the convergence of sub-networks belonging to the same PDE is considered. Figure 2 shows two Mobile Routers namely Mobile Router 1 (MR1) and also Mobile Router 2 (MR2) serving two different mobile sub-networks. In both mobile sub-networks, the mobility management is handled by the respective mobile router. As a consequence, the mobility of the mobile sub-network is transparent to the nodes behind the mobile routers.

Since, the objective of the simulation model is to evaluate the convergence of the mobile sub-networks, a pre-planned route was set for the mobile sub-networks. In Fig. 2, the convergence takes place in the second handover (Handover 2). It is assumed that at each handover, MR2 simply searches for another AR (also

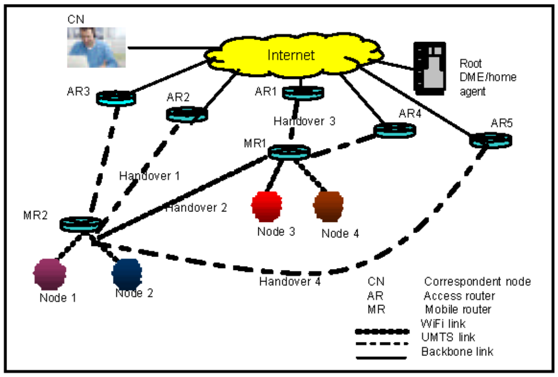

Fig. 2: The simulation model

known as the detection and search processes as mentioned by Velayos and Karlsson (2003). If a new AR is found in range, the mobile router sets up a new path and exchanges information with the new AR. Figure 2 shows that 4 handovers took place in the simulation. As mentioned by Velayos and Karlsson (2003) the handover process can be divided into three phases namely detection, search and execution. The time taken for the handover process as reported by Velayos and Karlsson (2003) is actually technology dependent, i.e. different wireless cards have different handover times.

The detection phase refers to the discovery of the need for the handover to be executed. Receiving a stronger router advertisement signal from the nearest router (even mobile router in this case) is one example. The second phase, i.e. the search phase, refers to the acquisition of the information needed to perform the handover. Lastly, the execution phase refers to the performance of the handover itself.

The de-convergence processes in the simulation model: After a certain time, the simulation model forces the converged mobile sub-networks to de-converge. In the simulation, the de-convergence process occurs during handover 4 (Fig. 2). For the nested approach this process is known as de-nesting and for the merged approach it is known as de-merging. The de-nesting process is actually the handover process of the child sub-network from the parent sub-network. The same procedure for handover applies here as mentioned in earlier. The de-nesting is actually a straightforward case of handover same as in the nesting process. The time taken to complete the de-nesting process is known here as de-nesting time and is represented by $T_{\text{de-nest}}$.

As for the de-merging process, it is a process of reconstructing a mobile sub-network. The de-merging process is more complicated than de-nesting. The mobile router will initiate the de-merging process. This is achieved through MR2 sends de-merging signals to all the nodes. In the scenario, the user walks away from the current mobile sub-network he/she is attaching to and taking with him/her a number of devices. These devices are the devices that will actually respond to the MR2 de-merging signals. The involved devices have to respond to the de-merging signal as that is the strongest signal they could receive from any AR or mobile router which is a normal procedure for a handover as mentioned by Velayos and Karlsson (2003).

Upon receiving the de-merging signal, a node will send a handover signal to the previous Mobile Router (i.e. MR1) and a DHCP request to the current mobile router it is attaching to (i.e. MR2). Each device that wants to be part of the newly reconstructed mobile sub-network has to do this. This is actually one of the disadvantages of the merged approach. The time needed to form and de-form a mobile sub-network has a linear relationship with the number of devices involved in the merging and de-merging process. As the number of devices increases, the time to merge and de-merge also increases. This will result in the increase in the number of signalling traffic.

Upon receiving the DHCP request from the devices, MR2 will send back a DHCP ack. Upon receiving the DHCP ack, the device will send a BU message to home agent via., MR2. In response, the home agent will send back BU ack to each of the device that sent BU message. The time taken to complete this process is known here as de-merging time and is represented by $T_{\text{de-merge}}$. Again here, the number of devices will also affect the number of DHCP ack that the mobile router (which received the DHCP request) would have to issue. As the number of devices increases, the signalling traffic would also increases.

Handover delay metrics derivation: Handover delay as given by Caceres and Padmanabhan (1998) can be defined as the amount of time where mobile node cannot receive data on its downlink, which results in disruption to the service or application running on the node. Based on the basic formula given by Caceres and Padmanabhan (1998), a handover delay formula has been formulated for the PDE-NEMO. The handover delay for PDE-NEMO is made up of two components namely rendezvous time (T_{Rndzvs}) and nesting/de-nesting ($T_{\text{Nest}}/T_{\text{de-nest}}$) or merging/de-merging time ($T_{\text{Merge}}/T_{\text{de-merge}}$). In the Eq. 1a-d, the handover delay can take any of the form below depending on which operation is being carried out.

$$T_{HO} = T_{\text{Rndzvs}} + T_{\text{nest}} \tag{1a}$$

$$T_{HO} = T_{\text{Rndzvs}} + T_{\text{de-nest}} \tag{1b}$$

$$T_{HO} = T_{\text{Rndzvs}} + T_{\text{merge}} \tag{1c}$$

$$T_{HO} = T_{\text{Rndzvs}} + T_{\text{de-merge}} \tag{1d}$$

For the merged approach, the handover delay refers to the total time for all the nodes involved to restore the traffic flow after the convergence or de-convergence and also the time needed to setup the new path/route for all the nodes. Of course the time taken to restore the traffic flow and also to setup the new path/route for each node differs. Conversely, for the nested approach, the handover delay refers to the time needed by a single mobile router to restore the traffic flow and also to setup new path/route.

The rendezvous time is the period that elapses between the moment the mobile sub-network roams out of the coverage area of the old access router and the moment when the new access router receives the path setup acknowledgment message sent by the mobile router or mobile node. In the simulation model, the handover delay is the major metric that contributes to the packet loss in both the nested and merged approaches.

On the other hand, T_{nest}, $T_{de\text{-}nest}$, T_{Merge} and $T_{de\text{-}merge}$ are actually the time needed to implement the nesting/de-nesting and merge/de-merge approaches. All of them refer to the time it takes to restore the traffic flow after the mobile sub-networks has converged or de-converged. This includes the delay incurred in setting the new path/route to point to the new location, i.e. latency due to any exchange of signalling messages, plus the time for the first downlink packet to reach a mobile host in the mobile sub-networks. In other words, it is the time needed to restore traffic flow to the mobile sub-network after it has moved to a new access router. Of course in the simulation model, the two different approaches proposed for the convergence of mobile sub-networks in the PDE would produce different results as will be discussed later in this study.

The T_{Nest} or T_{Merge} is equivalent to:

$$T_{nest} = T_{Path} + T_C \tag{2a}$$

$$T_{de\text{-}nest} = T_{Path} + T_C \tag{2b}$$

$$T_{merge} = (T_{path} + T_C)_n - (T_{Path} + T_C)_1 \tag{2c}$$

$$T_{de\text{-}merge} = (T_{Path} + T_C)_n - (T_{Path} + T_C)_1 \tag{2d}$$

For the merged approach, the number of devices involved in the merging and de-merging process does effect the time it takes to merge and de-merge. This is shown in Eq. 2c and d. T_{Path} is the time incurred in setting the new path/route to point to the new access router. While T_C is the time taken for the first downlink packet to reach the mobile host, also knows as the completion time. In Eq. 2c and d, the n represents the last mobile node to complete the merging/de-merging process while 1 represents the first mobile node to complete the merging/de-merging process. It is assumed that the mobile nodes that involved in the process are being dealt with in parallel.

In the merge approach, this is the number of nodes considered in the calculation, as each mobile node behind a mobile router is required to participate in the process. This contrasts with the nested approach. As with the handover delay, the merged/de-merged delay also is affected by the number of devices involved in the process. As the number of devices increases, the time it takes to merge and de-merge will also increases. This is shown through Eq. 2c and d whereby the time it takes for the n devices to merge or de-merged will obviously be greater if n is a greater number. In the formula, T_{Path} can be represented by:

$$T_{Path} = T_{BckPrcssng} + T_{BckLnk} \tag{3}$$

where, $T_{BckPrcssng}$ is the time required to process the IP packets in the backbone network and T_{BckLnk} is the delay encountered by a packet along the backbone network. The $T_{bckPrcssng}$ includes the time needed to process the IP packets in nodes like the access router and also routing processes such as route update in a node or switching/routing which involves route look up. Whereas, the T_{BckLnk} is the delay encountered by a packet along a link between 2 nodes.

The performance of handover in the context of this analysis can be said to be characterized by the handover delay. The handover delay has been determined in this research as the main cause of disruption to the IP services in the mobile sub-networks of a PDE. The disruption of IP service which is also known as service disruption time, is the time during which the mobile host cannot receive data on its downlink. The handover delay is the main reason for having packet loss in a handover. It was mentioned in the previous sub-section that in this research, the handover delay is also contributed by the time taken by the mobile sub-networks to converge and de-converge. Depending on which approach used, the time needed to converge and de-converge differs. That is why in Eq. 1a-d, the time needed to nest/de-nest and merge/de-merge are also considered.

The handover delay will result in packet loss during the handover process. The packet loss is the other performance metric that will be discussed in this research. Packet loss is determined by the time it takes for the new route-update to be activated. The number of packet loss can be minimized by minimizing the handover latency. In other words, it can be said that the loss of packets at handover is actually associated to the handover latency. It is the objective of this research to identify the convergence approach of mobile sub-networks which can offer minimal handover latency in order to obtain small packet loss ratio. The number of packet loss at handover η can be represented by:

$$\eta = \omega T_{HO} \tag{4}$$

where, ω is the rate of downlink packets (packets/sec).

This means that the packet loss at handover η is equal to the number of packets arriving at the old Access Router during the handover time T_{HO}. These packets are considered as lost as the old access router cannot forward the packet to its recipient node as the recipient node has moved away. There is no packet buffering whatsoever as the model uses the hard handover technique. How it works is that it will make contact with the new access router or mobile router only after breaking its connection with the serving access router. This is referred to as break before make connection. Since, the protocol is related with a mobile sub-network, therefore the number of packets lost during a session also needs to be calculated. Assuming that the mobile sub-network is moving and is engaged in an IP session of length λ_s, the number of handovers, μ, can be expressed by:

$$\mu = \frac{\lambda_s}{\tau_{cell}} \tag{5}$$

where, τ_{cell} is the cell dwell time.

From Eq. 4 and 5, the number of packets lost during a session can be calculated, i.e.:

$$\eta_s = \mu\eta \tag{6}$$

Prior to be able to calculate the packet loss ratio, the number of packets transmitted during a session (ζ_s) needs to be calculated first. The Eq. 7 is used for this purpose:

$$\zeta_s = \omega\lambda_s \tag{7}$$

Finally, from Eq. 6 and 7, the packet loss ratio, ϕ, can be calculated as given by the following formula:

$$\phi = \frac{\eta_s}{\zeta_s} \tag{8}$$

Cost analysis metrics derivation: Within the context of this research, cost can be defined as a representative value (number) which refers to the overhead in terms of latencies or delays associated with mobility of Mobile Sub-networks in the PDE-NEMO. In this research, the analytical model focuses on the signalling and database lookup costs for the handover that is/are taking place during the convergence and de-convergence of Mobile Sub-networks in the PDE. The cost analysis was also discussed by Reaz *et al.* (2006), Zhu and McNair (2005), Sabeur *et al.* (2006) and Mun and Jang (2005).

The signalling cost of a mobile sub-network in the PDE-NEMO has two major components namely: cost for path setup and cost for packet delivery. Both of these costs made up the signalling cost during the convergence and de-convergence of mobile sub-networks in the PDE. The signalling cost depends on a variety of factors, such as network topology and location of entities. However, in this research, the signalling costs used in the calculation of the performance analysis are based on the environment of the simulation model developed. In order to compute the performance analysis, the parameters shown below are used:

γ_{Nest} : Cost for path setup in the nested approach
γ_{Merge} : Cost for path setup in the merged approach
Ψ_{nest} : Cost of packet delivery in the nested approach
Ψ_{merge} : Cost of packet delivery in the merged approach

Let $Cost_{LU}$ be the cost per unit time for location update, then:

$$Cost_{LU} = \frac{\gamma}{T_{rsdn}} \tag{9}$$

where, T_{rsdn} is the residence time for a mobile sub-network.

Let $Cost_{PD}$ be the cost per unit time for packet delivery and ω is the rate of downlink packets (packets/sec) then:

$$Cost_{PD} = \omega\Psi \tag{10}$$

Therefore, the total cost per unit time for packet delivery and location update is:

$$\upsilon = Cost_{LU} + Cost_{PD} \tag{11}$$

Which is formulated for the different approaches as follows:

$$\upsilon_{Nest} = \frac{\gamma_{Nest}}{T_{rsdn}} + \omega\psi_{Nest} \tag{12}$$

$$\upsilon_{Merge} = \frac{\gamma_{Merge}}{T_{rsdn}} + \omega\psi_{Merge} \tag{13}$$

In order to calculate the path setup and packet delivery costs, the database lookup and signalling costs need to be determined as well. Both costs are represented by the following:

ξ_{HA} : Cost of updating/querying a database at home agent
ξ_{MR} : Cost for updating/querying a database at mobile router
$\ell_{int\,rnt}$: Cost for sending a signalling or data packet over the Internet
ℓ_{mobrtr} : Cost for sending a signalling or data packet between mobile routers

The signalling costs listed above include the switching/routing cost at all intermediate nodes and also the cost for transmitting the packet through the communication links. The cost of updating/querying at the home agent was based on the actual processing speed at the home agent. This includes the queueing time of the packets at the home agent. Whereas, the cost for updating/querying at the mobile router was based on the actual processing at the mobile router. This also includes the queueing time of the packets involved at the mobile router.

On the other hand, the cost of sending a packet over the Internet was actually derived from the actual time taken for the packet to travel the internet in the simulation model. The time was then weighed against the time taken to send packet between the mobile routers as a ratio. The valued obtained were 40 for the $\ell_{\text{int rnt}}$ and 1 for the ℓ_{mobrtr}.

The total time taken to do the updating/querying was then weighed against the time taken for updating/ querying at the mobile router as a ratio. This ratio was then used in the calculation. The ratio values obtained for the updating/querying the home agent and also the mobile router was too small as compared to the ratio values obtained for costs of sending a packet over the Internet and between mobile routers. Therefore, these values hardly have any affect on the delivery costs. The values of the parameters used in the calculation are as shown on Table 1.

Based on the nested and merged approaches algorithm discussed in section handling the convergence of mobile sub-networks in PDE, the expressions for location update and packet delivery costs for both approaches are derived as follows:

$$\gamma_{\text{Nest}} = \xi_{\text{HA}}+\xi_{\text{MR}}+2\ell_{\text{int rtr}}+2\ell_{\text{mobrtr}} \tag{14}$$

$$\gamma_{\text{Merge}} = n\,(\xi_{\text{HA}}+\xi_{\text{MR}}+2\ell_{\text{int rtr}}+2\ell_{\text{mobrtr}}) \tag{15}$$

$$\Psi_{\text{Nest}} = \xi_{\text{HA}}+2\xi_{\text{MR}}+2\ell_{\text{int rtr}}+2\ell_{\text{mobrtr}} \tag{16}$$

$$\Psi_{\text{Nest}} = \xi_{\text{HA}}+\xi_{\text{MR}}+\ell_{\text{int rtr}}+\ell_{\text{mobrtr}} \tag{17}$$

Therefore, by using Eq. 12-17, the total cost for the different approaches are given by the following expressions:

Table 1: Signalling cost parameters

Signalling cost parameters	Values
T_{rsdn}	150.00
ω	0.01
$\ell_{\text{int rnt}}$	40.00
ℓ_{mobrtr}	1.00

$$\upsilon_{\text{Nest}} = \left[\frac{\xi_{\text{HA}} + \xi_{\text{MR}} + 2\ell_{\text{int rnt}} + 2\ell_{\text{mobrtr}}}{T_{\text{rsdn}}}\right] + \left[\omega\left(\xi_{\text{HA}} + 2\xi_{\text{MR}} + \ell_{\text{int rnt}} + 2\ell_{\text{mobrtr}}\right)\right] \tag{18}$$

$$\upsilon_{\text{Merge}} = \left[\frac{n\left(\xi_{\text{HA}} + \xi_{\text{MR}} + 2\ell_{\text{int rnt}} + 2\ell_{\text{mobrtr}}\right)}{T_{\text{rsdn}}}\right] + \left[\omega\left(\xi_{\text{HA}} + \xi_{\text{MR}} + \ell_{\text{int rnt}} + \ell_{\text{mobrtr}}\right)\right] \tag{19}$$

ANALYTICAL RESULTS

After the performance metrics have been derived, it is time now for substituting some typical representative values into the equations. This will provide the basis for the comparison analysis. In the following sub-sections, a detailed analysis is carried out on this characterization of metrics.

Number of device effect on convergence time of mobile sub-networks in PDE: Figure 3 shows that, when the number of devices increases, the time taken to Nest is shorter than to merge. The nested approach actually was not affected by the increase of number of devices. This is due to the situation that only the child mobile router is involved in the nesting process every time. The variance of the nesting times comes from the random delay introduced in the simulation model associated with the commencement of the nesting process.

In contrast, the increment in the merging time was due to the increasing signals every time the number of devices was increased. Unlike the nested approach, previously described, every node is involved in the merging process hence, increasing the signalling involved. In the simulation model, the number of devices is restricted to 8 only as it is reasonable number for a person to have devices on him/her at one time. However, the number does not include other devices that belong to a person in his/her other non-mobile sub-networks.

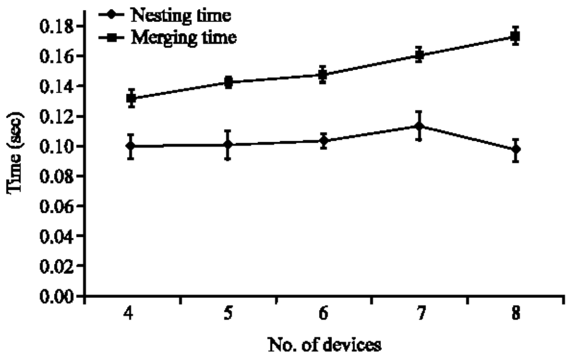

Fig. 3: Time taken to nest/merge as number of devices increases, with 95% confidence intervals

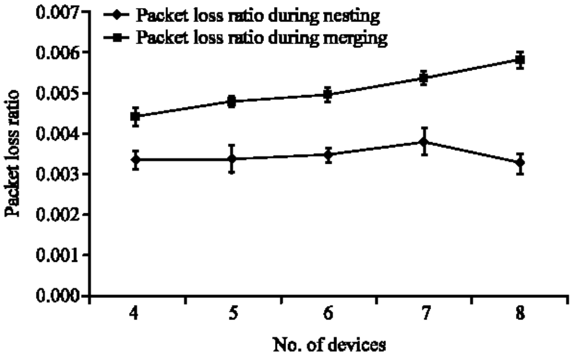

Fig. 4: Packet loss ratio during nesting/merging approach as number of devices increases, with 95% confidence intervals

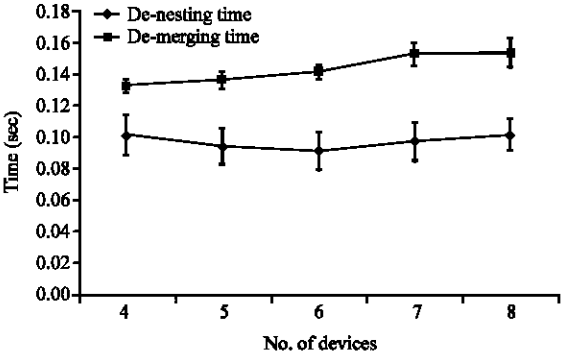

Fig. 5: Time taken to de-nest/de-merge as number of devices increases, with 95% confidence intervals

Figure 4 shows the packet loss ratio for both convergence approaches. A longer time was needed to perform the merging process than the nesting process. As a result, more packet losses were recorded at the old mobile router. The nested approach gives a lower packet loss ratio compared to the merged approach. Figure 5 shows that the time needed to perform the de-nesting process is shorter than the de-merging process. On the other hand, Fig. 6 shows that the packet loss ratio for the de-merged approach is higher due to longer time taken in the de-merging process as the number of devices increases.

Based on the results shown in Fig. 3 and 5, the merged approach took longer time in both merging and De-Merging and thus results in a higher packet loss. The packet loss figures are shown in Fig. 4 and 6. In order to calculate the packet loss ratio, Eq. 8 was used. The time taken when the mobile sub-networks converge is one of the metrics used to compare the nested and merged approach. It was observed that the increase in the number of devices did not have any effect on the nesting and de-nesting process.

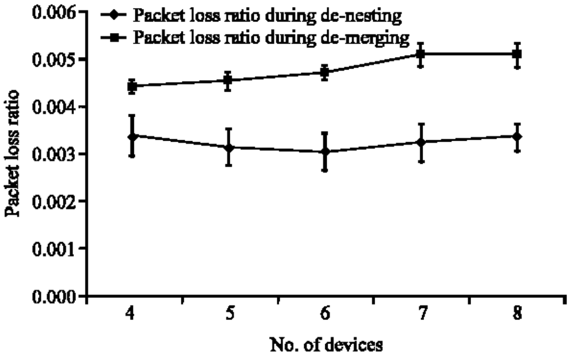

Fig. 6: Packet loss ratio during de-nesting/de-merging approach as number of devices increases, with 95% confidence intervals

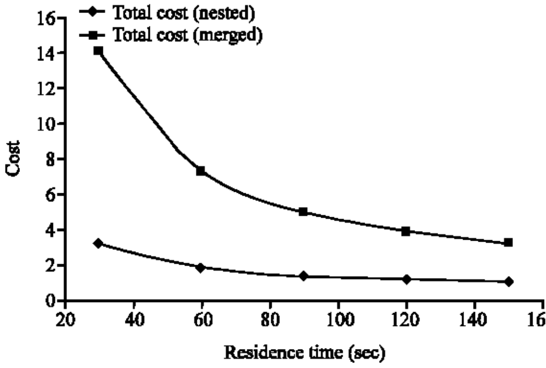

Fig. 7: Effect of residence rime on signalling cost with number of nodes = 5

Although, there are some differences in the amount of time needed to perform both processes, but the differences are based on the random number generator used to generate delays involved in the model. Figure 3 and 5 show clearly that there is no linear trend in nesting and de-nesting when the number of devices increases.

Cost analysis results: Within the context of this research, cost can be defined as a representative value (number), which refers to the overhead in terms of latencies or delays associated with mobility of mobile sub-networks in the PDE-NEMO basic support protocol. For the cost analysis, it was assumed that the signalling cost dominates with the database access cost was set to 0. All the parameters values within Eq. 18 and 19 were obtained from the simulation model developed. The values were then substituted into the equations to obtain the final results as shown in Fig. 7 and 8. The values for the cost of sending packets through the Internet and also between mobile routers were obtained after the actual times were measured from the simulation model.

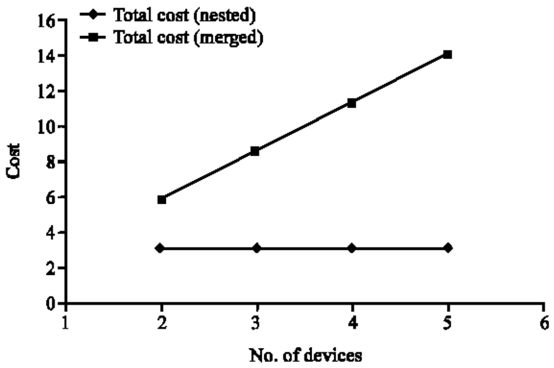

Fig. 8: Effect of number of devices on signalling cost

Figure 7 shows the effect of residence time on the signalling cost. It was observed that the signalling cost for the merged approach is greater than the nested approach. With the decreasing of the residence time, the cost for location update for the merged approach is relatively high compared to the nested approach, which results in a higher increase of signalling cost. However, it was observed that both approaches have the same performance characteristics when the residence time decreases. From Fig. 7, it can be deduced that when mobility decreases, the signalling cost also decreases for both approaches. This actually makes sense as the less number of handovers take place, the less number of signalling will take place. This applies to both the approaches proposed to handle convergence and de-convergence of mobile sub-networks in the PDE. The only different is that the nested approach will generate fewer signals as compared to the merged approach.

DISCUSSION

In the simulation model, the proposed protocol has been implemented in supporting the mobility of mobile sub-networks in the PDE. The proposed protocol has also been used to handle the convergence of mobile sub-networks. In handling the convergence of mobile sub-networks, two approaches have been proposed and implemented in the simulation model.

In the merged approach, the number of devices did have effects in its formation and deformation. This is due to the number of signals involved in merging and de-merging process. The number of signals involved increases as the number of devices increases. This is part of the requirement of the merged approach itself. In the merged approach, each device in the mobile sub-network has to send a binding update to the root DME whenever a handover is taking place. This is opposed by the nested approach whereby only the mobile router sends the binding update during a handover process.

The other metric used to compare the nested and merged approach is the packet loss ratio during the convergence and de-convergence processes. The packet loss ratio is related to the handover delay. The longer time taken in the handover delay, the higher the packet loss ratio. The packet loss ratio for the Merged approach (for both merging and de-merging) are higher than in the nested approach. The high packet loss ratio in the merged approach was contributed by the longer handover time. As the number of devices increases, the handover delay in the merged approach also increases as was explained earlier. This contributed the longer handover delay and hence to the higher packet loss ratio.

Theoretically, compared to the nested approach, there would be more signalling needed in the merging process. Each device will introduce its own signalling traffic. The increase in the number of devices involved in the merging process will increase the signalling traffic as well. This is due to the signalling traffic contributed by the de-registration process which all the devices in the incoming mobile sub-network has to take up. The de-registration is needed as a result of the changes of home addresses (in the context of a PDE) of the devices. In this approach, all the devices would have to request for new home addresses.

For the merged approach, as the number of devices increases, the signals involved also increases. The nested approach seems to alleviate this problem by performing a simple convergence process without involving the mobile hosts behind the mobile router during the convergence process. On the contrary, in the Merged Approach, whenever the mobile sub-networks become converged, all the nodes behind the mobile router have to participate in the convergence process. As a result, the number of signalling packets increases as the number of nodes increases.

This is one of the drawbacks of the merged approach, i.e. generating excessive signalling cost due to its mechanism. Besides increasing the signalling cost, the same mechanism also causes the handover delay for the approach to be higher than that of the nested approach as been discussed in section number of device effect on convergence time of mobile sub-networks in PDE. As a result, the packet ratio for the merged approach is also higher than the nested approach. As a result, the merged approach generates more signalling cost as the number of devices increases. The increment can be said as a linear relationship.

As for the nested approach, the signalling cost remains constant although the number of devices increases. This is due to the mechanism of the nested approach whereby only the mobile router is involved in the convergence and de-convergence processes. As a result, the number of devices behind the mobile router does not affect the overall signalling cost during the convergence and de-convergence process.

From the experiments conducted using the simulation model, the proposed protocol managed to provide the mobility management needed by the mobile sub-networks in the PDE. In addition, the proposed protocol has also managed to handle the convergence of mobile sub-networks. In fact, two approaches have been proposed. However, only one of the two approaches would be used. it is obvious that the nested approach is the approach that would be used in the implementation of the proposed protocol.

There was no previous work done in supporting the mobility of mobile sub-networks in the PDE. Hence, the proposed protocol could be seen as essential in making the PDE into a reality. One thing that has to be kept in mind is that the proposed protocol is an adaptation of the IETF's NEMO protocol. Due to the different services provided by the PDE, therefore, certain things like new data structure and new signalling were incorporated into the IETF's NEMO protocol in order to come up with this PDE-NEMO protocol.

CONCLUSIONS AND FUTURE WORK

In this study, the performance evaluation between the two approaches proposed to handle the convergence and de-convergence of mobile sub-networks have been discussed. The simulation model and its environment was also explained and followed by the discussion of the implementation of both approaches in the model. The performance metrics used to evaluate both approaches were also presented together with its derivation. This was followed by the results of the evaluation.

As a conclusion, it is safe to conclude now that the nested approach is more favourable than the merged approach in handling the convergence of mobile sub-networks in the PDE. The nested approach has less signalling traffic as compared to the Merged approach in handling mobile sub-networks convergence. This was evident in the experiment whereby the nested approach has shown that the convergence time remained the same although the number of devices had been increased. Lesser signalling traffic in the nested approach would only mean shorter nesting/de-nesting time. In addition, the nested approach has also produced lower packet loss ratio which was contributed by the fact that is has a simple mechanism in handling the convergence of mobile sub-networks.

On the other hand, the merged approach although has proved that it can handle the convergence of mobile sub-networks, but the outcome is not as attractive as the nested approach. In the merged approach, more signalling traffic is needed since the nature of the approach required that all the devices within a mobile sub-network to manage their own mobility. This has contributed to longer merging/de-merging time. As a result, as the number of the devices increases in a mobile sub-network, the signalling cost, the convergence time and the packet loss ratio also increases.

Although, the protocol proposed in this research managed to provide mobility management for mobile sub-networks in the PDE, however, it has not covered the route optimization which is seen as essential in a real-time traffic environment. The next step for this research is to look into this matter.

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