Analytical Evaluation of Dynamic Proxy Assisted Mobility Support in P2P Networks


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Abstract—In recent years peer-to-peer communications has developed into a powerful networking model for real-time applications. Its slow adoption by the wireless community can be attributed to several factors including resource limitations of portable devices and restrictive pricing models employed by operators. The mobility management strategy proposed in [1] alleviates some of these problems by allowing migration of proxy services to the local vicinity of a mobile peer whilst helping to reduce the traffic transmitted over the wireless link. In this paper, we analytically evaluate the above-mentioned scheme by formulating the performance metrics of registration cost and message delivery cost. Specifically we employ the random walk model to represent the motion of a mobile peer moving between different subnets. Our results show that considerable performance improvements, up to 80% in some cases, can be achieved in most mobility scenarios.

I. INTRODUCTION

The Peer-to-Peer (P2P) networking paradigm has emerged as an important and effective mechanism for content dispersion and building collaborative networks. Current research efforts into real-time user applications such as Internet telephony and online gaming applications employ P2P concepts at the core of their networking model. The growth of wireless communications has fuelled significant research into mobility management solutions for portable nomadic devices. The adoption of the peer-to-peer networking model by the wireless community has been stifled by the several factors including hardware limitations on mobile devices, metered pricing models employed by operators, low bandwidth and unpredictable connectivity.

Network layer solutions provide an effective infrastructure solution, but sole reliance on network layer mobility management strategies is insufficient. All P2P networks build a virtual topology which sits on top of physical network and hence requires additional services to organise the topology during a mobility event. In [2] and [3] solutions involving surrogates and proxies respectively are presented. In both solutions the surrogate or proxy locations and operations are kept separate from the network topology. This may result in counter productive routing strategies for messages which are compelled to negotiate these entities to reach their destinations. Therefore, in [1] and [4] we proposed a new mobility extension based around the JXTA P2P networking architecture. Our aim was to create a mobility management strategy that could co-exist synergistically with existing network mobility management protocols.

Little research has been done in evaluating the performance, scalability and practical large scale deployment of these surrogate/proxy infrastructure support models. In [1] and [4] we analysed the performance of the dynamic proxy scheme using simulation. The simulation approach restricted the size of the networks and the associated number of mobile nodes. Although the simulation approach allowed us to investigate finer more intricate details such as message delivery latency and message inter-arrival time, it was difficult to obtain a macroscopic understanding of the impact of locating proxies at strategic locations inside the access network. Therefore, in this paper we investigate analytically the performance of our proposed solution in terms of hand-over delay and message delivery cost. The proposed analytical model will aid in the planning and deployment of a scalable proxy infrastructure to support resource limited mobile peers within an access network. The emphasis of the contribution is to evaluate the effectiveness and investigate the influence of parameters such as the size of the proxy regions and the mobility rate on the scalability and efficiency of the infrastructure.

II. THE ARCHITECTURE

The architecture is based on the concept of proxies providing a gateway for resource limited mobile nodes to connect to the P2P network. Mobile Peers (MP), connect to and participate on the overlay network via the proxy. Hence, all traffic is routed through the proxy to MPs. As such, the distance between the proxy and the MPs is critical to the response time observed by the end user. Upon an initial lease negotiation for the proxy services, a proxy creates a profile for the mobile peer. As the peer moves within an access network, obtaining new IP addresses as it changes access points, the optimum proxy is obtained via the existing P2P service discovery protocols.

In order to minimize the impact of the existence of the proxy in the communication path, we propose to move the services provided by the proxy as closer to the current position of the MP. This entails resuming all communication sessions at a proxy closer in proximity to the current location of the MP. In order to provide uninterrupted service during the switch over, we provide for buffers in the proxies and message forwarding mechanisms between the proxies. A detailed description of the message structures and simulation results are provided in
[4]. Fig 1, shows the messaging sequence involved in profile migration as described in [4].

Fig. 1. Signalling sequence during handover between proxies

III. MOBILITY MODEL

The mobility model chosen is based on the work done by Fang et al. in [5] and later by Galli et al. in [6], [7]. In [6] and [7], Galli et al. presents a model for evaluating different mobility protocols. Under the assumption of a random walk mobility model and transmission cost proportional to distance, a closed form expression to quantify the average handoff delay, was obtained. We extend this model to support a two-tier hierarchical structure consisting of a group of proxies located on the upper level and the mobile peers located on the lower level. The mobile peers are free to move between subnets which are abstracted to tessellating, identically sized cells in a grid configuration. The proxies are also arranged in a grid configuration in which the region encompasses one or more subnets as shown in Fig 2. Analogous to hierarchical mobile IP, the subnets that fall under this region are assumed to be under the control of that particular proxy. This implies that all P2P communication traffic originating from the related subnets must pass through the proxy. In our random walk model, the

movements of the user are constrained to either horizontal or vertical shifts only. Therefore, the distance between any two cells with coordinates represented by \((x_1, y_1)\) and \((x_2, y_2)\) is given by \(|x_2 - x_1| + |y_2 - y_1|\). A movement from the residing cell to one of its four neighbouring cells represents a user moving from one subnet to another. We must assume that the subnet coverage does not overlap and are confined to the rigid shape of a square cell. After each movement, the mobile must undergo an IP configuration phase during which it acquires a new IP address which contains the subnet prefix. Although lower layers such as physical, data link, network layer and transport contribute to the overall costs and delays, our analysis ignores these parameters instead focussing on the application layer signal propagation and processing overhead influencing hand-over delays and registration costs on mobility management strategy.

The entities involved in the proposed management infrastructure and strategy and the distances between them with relation to each other are shown in Fig 3. We assume a lightly loaded network where the delay between any two neighbouring nodes is considered to be constant. The distance between any two nodes is represented as a collection of hops between routers and assumes that the routers can only route/forward traffic to neighbours that are either horizontally or vertically next to it. The upper layer of the two-tier hierarchical model consisting of the proxies must form a coherent pattern that can be overlayed on top of the lower layer. The correlation between the layers is illustrated in Fig 2. We assume that all the subnets are grouped into regions of equal size dictated by the parameter \(a\). The parameter \(a \) represents the diameter of the regions. Equation (1) produces a set of co-ordinates which denote the locations of the proxies in the upper right hand (1st) quadrant of a grid of size \(d\) for a deployment of proxies with a regional radius of \(a\) as shown Fig 4(a).

\[
y = \left( -\frac{a}{a+1} \right) x + \left( \frac{p}{a+1} \right),
\]

where \(x = s, s + (a + 1), s + [2(a + 1)], s + [3(a + 1)], \ldots d\) and \(p = a^2 + (a + 1)^2, 2[a^2 + (a + 1)^2], \ldots d\). A set of complex numbers \(V\), is constructed using the \([x, y]\) co-ordinate set obtained from (1) as shown in (2). To obtain a set consisting of proxy locations in all four quadrants of the grid, the

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>No. of hops from Mobile Peer(MP) to Correspondent Peer(CP)</td>
</tr>
<tr>
<td>k1</td>
<td>No. of hops from Mobile Peer(MP) to the Proxy Peer(PP)</td>
</tr>
<tr>
<td>k2</td>
<td>No. of hops from Mobile Peer(MP) to the Proxy Peer(PP)</td>
</tr>
<tr>
<td>n1</td>
<td>No. of hops from Proxy Peer(PP) to Correspondent Peer(CP)</td>
</tr>
<tr>
<td>n2</td>
<td>No. of hops from Proxy Peer(PP) to Correspondent Peer(CP)</td>
</tr>
<tr>
<td>(C_{proc})</td>
<td>Processing cost of single message at a peer</td>
</tr>
<tr>
<td>(C_{tx})</td>
<td>Transmission cost of one message over one hop</td>
</tr>
<tr>
<td>(P_c)</td>
<td>The cost of a profile</td>
</tr>
</tbody>
</table>

Fig. 2. The two-tier hierarchical model

Fig. 3. Relative distances between the entities involved in a session between a mobile peer and a fixed correspondent peer

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coordinates obtained from (1) are transposed by 90°, 180° and 270° degrees for quadrants 2, 3 and 4 respectively. This is achieved by multiplying the complex number set given by (2) by multiples of i as shown in (3).

\[ V = x + iy \]  \hspace{1cm} (2)

\[ P = \left\{ \text{Re} \left( v, i^{(n)} \right), \text{Im} \left( v, i^{(n)} \right) \right\} \text{ where } 1 \leq n \leq 3 \text{ for } \forall v, \]  \hspace{1cm} (3)

where \( \text{Re}(v) \) and \( \text{Im}(v) \) denotes the real and imaginary parts respectively of the complex number \( v \).

IV. REGISTRATION COST

In this section we develop cost functions for the registration procedures involved in the mobility management scheme. Evaluating the work done in [1] and [4] from an analytical perspective, we consider two schemes: static and dynamic deployment of the proxies.

In the static mode, location update messages are sent to the designated proxy. The proxy services remain fixed to a particular location, therefore, as the MP begins to move further away from its original location, the distance over which the location updates must traverse increases. We obtain the average cost of this location update given that the MP is free to move within the region that is encompassed by the movement threshold \( d \). The cost of the endpoint update to the proxy is given by:

\[ EU(k) = 2(k + m)C_{tx} + C_{proc} \]  \hspace{1cm} (4)

The dynamic proxy model gives rise to two distinctive mobility events, local and global. The local mobility event has the same cost function as that for the static model given in (4). Local mobility events are triggered when the MP moves to a new subnet that is within the region under the control of its existing proxy.

A global mobility event has three components: an endpoint update (EU) initiated from the MP and sent to the proxy, the cost of which is given by (4) where \( k = k2 \), a profile transfer (PTR) from the MP’s old proxy to its target proxy and correspondent updates (CU) from the old proxy to each correspondent node participating in the session.

\[ PTR(i) = 2aP_{c}C_{tx} + 2C_{proc} \]  \hspace{1cm} (5)

\[ CU(l) = 2(l(C_{tx} + C_{proc})) \]  \hspace{1cm} (6)

Global mobility events are triggered when the MP moves to a subnet that is outside the region of its current proxy. Hence, its is necessary to transfer the profile of the MP to the proxy that is responsible for the MP’s new subnet. Transfer and activation of the profile necessitates the transmission of correspondent updates to inform the CPs of a change in the location of the proxy service.

V. MESSAGE DELIVERY COST

In this section we develop a function for the message delivery cost based on the distance a message has to travel in order to reach the MP from the CP and vice versa. In both schemes being evaluated, the message must be intercepted by the proxy, translated and relayed. For the static proxy scheme, it is evident that the distance between the proxy and CP remain constant for the duration of a session and is given by \( n1 = (|k1| + |l|) / 2 \). The distance between the proxy and the MP \( k1 \) varies according to the location of the MP.

The dynamic proxy scheme introduces variability into both the distance from the MP to the proxy and the proxy to the CP. The distance between the proxy and the MP, \( k2 \) is determined by the proximity of the MP to its closest proxy. Additionally, when the MP changes proxies, the distance from the proxy to the CP changes and is given by \( n2 = (|k2| + |l|) / 2 \).

The message delivery cost function is given by:

\[ MDC(k, l) = (k + l)C_{tx} + C_{proc}, \]  \hspace{1cm} (7)

where \( k \) and \( l \) represent the distances MP-PP and PP-CP respectively subject to the scheme being analysed.

VI. AVERAGING OVER \( d \) MOVEMENTS

In this section we develop a model for averaging the respective costs over \( d \) consecutive random walk movements of the MP. For the static proxy scheme, we adopt the model presented by Galli et al. in [6]. The MP is initially modelled as being at the centre of a grid of size \((2d + 1) \times (2d + 1)\). Since we are interested in the cost associated with the MP being at a particular distance away from the proxy and not its particular location, we average over all possible locations of the proxies. We also average over all possible locations of the MP after \( d \) moves, allowing for a final result that represents the cost relative to the respective distances that is independent of the specific locations of either the MP or PP.

For the dynamic proxy deployment scheme analysis we use sets to note the co-ordinates of the proxies and the MP coordinates. We derive a method to obtain a set, \( M \) containing the possible locations of the MP after \( d \) movements. Provided that the MP is permitted to return to a subnet once having left it, the possible locations of a MP after \( d \) movements is:

\[ M(d) = \{ [m1, m2] \mid |(m1 - m2) \leq d \} \]  \hspace{1cm} (8)

For the assumed random walk mobility model where the MP is permitted to travel to one of its four neighbouring cells with an equal probability of \( \frac{1}{4} \), the probability of being in a particular cell, \((i, j)\) after \( n \) number of random walk movements can be
expressed by the following:

$$L_{i,j}^n = \begin{cases} \frac{1}{2^n} \left( \frac{n}{n+i+j} \right) \left( \frac{n}{n+i-j} \right) & \text{mod}(n + i \pm j, 2) = 0 \\ 0 & \text{otherwise} \end{cases}$$

(9)

where \( \binom{n}{n+i+j} \) is the binomial coefficient of the \( n \) choose \( \frac{n+i+j}{2} \).

In order to identify the location of the closest proxy to the MP, we compare the distances of the elements in set \( P \) with respect to the location of the MP, \( (m_i, m_j) \). The co-ordinate set which results in the minimum distance to the MP represents the closest proxy to the MP and is defined by:

$$C(i,j,P) = \{ [c_i, c_j] \mid \min(|i-p_i| + |j-p_j|) \}$$

(10)

There are a maximum of four locations at which the MP could have been prior to moving into its current subnet \([m_i, m_j]\). Therefore, we obtain the co-ordinates of its previous locations as follows:

$$M'(m_i, m_j, d) = \left\{ \left[ m_i', m_j' \right] \mid (|m_i + m_j - 1| < d) \right\}$$

(11)

There are two possible events that can occur after a MP movement: a local update or a global update. It is necessary to identify which cost function applies to the said movement. The two possible events relate to whether the last movement resulted in the MP moving out of the region of its current proxy. If such an event occurred, a profile migration is triggered, which we collectively define as a global update event. The second type of event which could occur involves the MP remaining within the region of its current proxy resulting in a local update event which results in an EU being sent by the MP to its current PP. Hence, the cost function is defined in (12).

$$CC(k', k_2, l, a) = \begin{cases} \text{PTR}(a) \text{ } + \text{EU}(k_2) \text{ } + \text{CU}(a) & k_2' < a \\ \text{EU}(k_2) & \text{otherwise} \end{cases}$$

(12)

where \( k_2' = \left| m_i' - c_i \right| + \left| m_j' - c_j \right| \) and \( k_2 = \left| m_i - c_i \right| + \left| m_j - c_j \right| \). The co-ordinates \([c_i, c_j]\) represent the location of the closest proxy to the current location \([m_i, m_j]\) of the MP given by (10). If \( k_2' \) exceeds \( a \) indicating that the MPs previous location was outside the region of its current proxy, a global update event takes place. Averaging over all possible previous locations of the MP we arrive at Average Cost Metric (ACM):

$$ACM(MN \text{ in } (m_i, m_j) \text{ after } d \text{ moves})^{(\forall M')} = \frac{1}{|M'|} \sum_{\forall M'} CC(k_2, k_2, l, a)$$

(13)

where \(|M'|\) denotes the cardinality of set \( M' \) and \((\forall M')\) denotes the averaging of the cost over all possible previous locations of the MP given it current location \([m_i, m_j]\). The cost in (12) is conditional upon the MP being at a specific location \([m_i, m_j]\) after \( d \) consecutive movements. In order to obtain a cost that is independent of the specific location of the MP, we weight the cost in (12) by the probability of the MP being at a location \([m_i, m_j]\) and sum over all possible locations of the MP after \( d \) consecutive random walk movements.

$$ACM(\text{After } d \text{ moves})^{(d)} = \sum_{\forall M'} \frac{d^d}{|M'|} ACM(MN \text{ in } (m_i, m_j) \text{ after } d \text{ moves})^{(\forall M')}$$

(14)

where \( L_{m_i, m_j}^d \) given by (9) denotes the probability that the MP will arrives in cell \([m_i, m_j]\) after \( d \) consecutive random walk movements. In order to work out the average cost per movement we average the cost in (14) by the number of consecutive movements, \( d \):

$$ACM_{(d)}^{(d)}(k) = \frac{1}{d+1} \left[ CC(0, 0, l, a) + \sum_{h=1}^{d} ACM(\text{After } h \text{ moves})^{(h)} \right]$$

(15)

where \( CC(0, 0, l, a) \) represents the cost when the MP arrives at the origin \((0,0)\) of the grid at the \( 0^{th} \) movement. The distances \( k_2 \) and \( k_2' \) are both zero as the MP is in the same cell as that of its proxy and does not have an associated previous proxy.

VII. ANALYTICAL RESULTS

In this section we present the results of a comparative analysis of the two proxy deployment strategies. With respect to the cost of registration and handling of mobility updates; the total sum of the individual components involved in the handling of a global mobility event is significantly greater when compared to the simple endpoint updates associated with the static proxy deployment scheme. But there is a substantial reduction in the routing distance over which the control messages travel.

As stated in [6] in analysing the ratio metric, we have overcome the need to assign absolute values to processing and transmission costs. Under the assumption of a lightly loaded network we are able to assume that \( C_{\text{proc}} = C_{\text{tx}} = 1 \) and the cost of the wireless transmission is assumed to be twice that of a wired transmission (\( m = 2 \)). Fig 5 shows a mesh plot of the Message Delivery Cost (MDC) ratios of \( \frac{MDC_{\text{Dynamic}}}{MDC_{\text{Static}}} \) as the distances \( k_1 \) and \( l \) are varied for different values of \( a \). It is clear from the figure that the message delivery cost of the dynamic scheme never exceeds that of the static scheme since the plots for all values of \( a \) remain below 1. The performance of the static scheme begins to degrade as the distance from the MP to the PP, \( k_1 \) increases. For small values of \( k_1 \), the dynamic scheme is comparable in performance to the static scheme even as the value of \( l \), the distance from the MP to CP, increases. The dynamic scheme begins to show significant improvement as the ratio of \( k_1 \) to \( l \) increases, highlighting the effectiveness of the scheme in minimising the impact of messages having to negotiate the proxy enroute to the MP. Further, as the size of the proxy region, \( a \) increases we observe that the performance of the dynamic scheme begins to degrade gradually. This is
attributable to an increase in the routing path length caused by the enlargement of proxy regions.

Fig 6 shows a plot the Total Cost (TC) ratios of $(TC_{Dynamic}/TC_{Static})$ for varying values of $k$ and $l$ evaluated under various sizes of proxy region. The TC is the combined cost of registration and message delivery. From the figure it is clear that the static scheme shows a gradual improvement in performance as the ratio of $l/k1$ increases. A maximum of a 20% improvement is achieved at the highest $l/k1$ ration, 20. This result indicates that the static scheme is better suited for MPs with a very limited range of mobility of approximately 2-3 subnet crossings per session.

![Fig. 5. Comparison of message delivery cost](image5)

![Fig. 6. Comparison of combined cost of registration and message delivery](image6)

VIII. CONCLUSION

In this paper we investigated the advantages of a mobility management scheme for peer-to-peer networks introduced in [1] compared to existing solutions that utilise proxy services which are fixed at particular peer in the network. We have shown that notable advantages in terms of route optimisation and an overall reduction of control signalling is achieved. Network layer mobility support has not been assumed and the dynamic proxy operation scheme is solely reliant upon the peer-to-peer network itself for mobility management and route optimisation. In [1] and [4] we analysed the performance of the proposed dynamic deployment scheme focussing on its deployment and utilisation within a single access network. In this paper we have been able to extend the investigation to include inter-domain and inter-access network scenarios where the MP moves between subnets which are administered by different organisations. We can conclude that the dynamic proxy scheme provides efficient mobility management support for peer-to-peer networks including route optimisation resulting is reduced message delivery latencies. The results indicate that the performance benefits that can be gained from the dynamic scheme are dependent on both the range of mobility and the frequency of change of point of attachment. Highly mobile peers will require larger proxy regions to counterbalance the overhead of profile migration, where as peers with a low mobility will benefit from the improved message delivery latencies gained by keeping the proxy regions small. It must be noted that the proposed scheme is customised to support mobility management specifically for peer-to-peer networking and is not an attempt to provide a generalised solution mobility management. This paper contributes an analytical model which will aid in the planning stages for the deployment of proxies to support resource constrained mobile devices running real-time applications.

Finally, it must be conceded that the analytic model used for evaluating the dynamic scheme is not tractable for large values of $d$. Therefore, our future work will involve developing a more tractable model.

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