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Scalable delivery of immersive communication environment (ICE) using peer-to-peer (P2P) architecture

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Abstract—In this work, we propose a Peer-to-Peer (P2P) voice delivery architecture for the support of an Immersive Communication Environment (ICE). An ICE service allows multiple users in a Distributed Virtual Environment (DVE) to exchange live voices which are rendered with the directional and distance cues corresponding to the users’ positions in the DVE. Our architecture addresses the scalability issue in peer access bandwidth consumption encountered by the “brute force” full-mesh P2P architecture. On the other hand, our P2P architecture seeks a good balance between access bandwidth scalability and the voice quality delivered. The three key aspects of voice quality considered are voice transmission delay, directional voice rendering accuracy and voice attenuation accuracy. Our P2P architecture achieves access bandwidth reduction by organising all the pair-wise close peers into non-overlapping clusters and by mixing the voice streams within the same cluster so as to reduce the number of direct peer to peer voice exchanges. Different sets of experiments were conducted to compare the performances of our P2P architecture against the benchmark of the full-mesh P2P architecture.

Keywords: VoIP Service for Online Gaming, Peer_to_peer Network Services for Multimedia Communications

I. INTRODUCTION

Recently, networked voice communication services in Distributed Virtual Environments (DVE) have attracted much research interest [1] [2] [3]. One typical example of DVE is Multi-player Online Games (MOG) such as Lineage II which had 2.1 million subscribers in January, 2005 [4]. Each DVE user is represented by an avatar in the virtual world. In the context of this work, there is a one to one correspondence between an avatar in the virtual world and a peer platform in the physical network. For clarity, we use the word peer only. The close interactions and co-operations between avatars in a DVE are likely to be improved with the addition of a multi-party immersive voice communication service, which immerses each avatar in a personalised auditory scene. The auditory scene for a particular avatar is a mixture of the voice streams from all the surrounding avatars in that avatar’s hearing range. Each of these voice streams is directionally rendered and distance-attenuated according to the corresponding speaking avatar’s position in the DVE. We refer to such a multi-party immersive voice communication service as an Immersive Communication Environment (ICE). Most of the Voice-over-IP (VoIP) systems currently in use with DVE deliver a party-line mixture of voice streams which contains no directional or distance cues as offered by ICE [5] [6] [7]. Our ICE system is transparent to the underlying Virtual World Applications. ICE can be either an add-on service to a Game State Server or incorporated as part of the Game Engine, e.g. the text messaging service in World of Warcrafts. ICE can be applied to any applications with avatars moving in a virtual world with defined coordinates.

Most of the aforementioned VoIP systems used for DVE are supported by the full-mesh P2P architecture. In a full-mesh P2P architecture, all the communicating peers exchange voice streams directly with each other. Hence, the full-mesh P2P architecture offers the best voice transmission delay performance [1]. However, when implementing the full-mesh P2P architecture using multiple uni-cast flows, on average, each peer must download and upload one voice stream from each peer in its hearing range. Therefore the access bandwidth consumption at each peer scales up linearly with the peer density D which is the average density of each peer’s hearing range. Skype [6] adopts an architecture in which the peer clients with more processing and access bandwidth capacity automatically become super peers. Each super peer acts as a mixing node for all other peers in its hearing range. Skype reduces the demands on the access bandwidth of some peers but at the expense of the super peers. Consequently, Skype does not reduce the total number of voice exchanges required. Our proposed P2P architecture aims to address the access bandwidth scalability problem inherent in the full-mesh P2P architecture. Our P2P architecture clusters together pair-wise close (by virtual world distance) peers and mixes the co-cluster peer voice streams, thus reducing the number of direct peer to peer voice exchanges. Our cluster-based P2P architecture seeks a good balance between system scalability in terms of access bandwidth consumptions and the voice qualities delivered. The key voice quality requirements addressed in this work are, the voice transmission delays, directional voice rendering error and voice distance attenuation error. Moreover, in the actual routing of voice streams, we consider the important issue of even distribution of individual access bandwidth consumptions (nodal stress) between the peers.

II. CLUSTER FORMATION

A. Cluster Formation

Due to the large complexity in an optimal formulation (at least a quadratic linear programming problem), we devised two formulations which work in tandem together to provide a sub-optimal yet more scalable solution to the problem of peer clustering. In the first stage, the Initial Cluster Formation Formulation finds the largest initial cluster around each peer (N initial clusters in total) in which the virtual world distances between all the pairs of peers are within the pre-defined pair-wise distance constraint. We always set the pair-wise...
**distance constraint** to be less than the maximal hearing range of a peer so that all the peers in the same cluster can hear each other. In the second stage, the **Final Cluster Formation Formulation** chooses to establish a subset of **final clusters** from the **N initial clusters** provided by the first stage. In the second stage of clustering, each peer is assigned to just one **final cluster**.

### B. Inter-Cluster and Intra-Cluster Voice Exchanges and Renderings

There is no distance attenuation error introduced within the cluster. We define the directional voice rendering error using the concept of **acceptable voice rendering error** described in [8]. High quality voice streams are delivered to the peers residing in the same cluster because they are close to each other as bounded by the **pair-wise distance constraint**. However, not all the peers located close to each other are enclosed in the same cluster. In Fig. 1, peers $P_2$ and $P_3$ are close to $P_1$ (within the **pair-wise distance constraint**) but are not enclosed in $C_1$ with $P_1$. This could be because during the **initial cluster formation**, $P_2$ and $P_3$ are found to be not close enough to other peers in $C_1$. Alternatively, $P_2$ and $P_3$ could have been in the same **initial cluster** as $P_1$ but they were not assigned to the same **final cluster** as $P_1$ due to the need to balance between cluster size and the number of clusters (see A in Section V).

![Inter-cluster and intra-cluster voice exchanges and minimal delay routing](image)

**Fig. 1 Inter-cluster and intra-cluster voice exchanges and minimal delay routing**

At the completion of the final cluster formation process, the peers heard by a given peer $P_1$ are enclosed in one or more surrounding clusters. In turn, $P_1$ receives one mixed voice stream from each of these surrounding clusters. Hence, our clustering model replaces some of the full mesh voice exchanges performed at each peer with the bandwidth-efficient inter-cluster voice exchanges. In the scenario depicted by Fig. 1, peer $P_1$ in cluster $C_1$ receives one mixed voice stream $MV_1$ (mixture of the voices of $P_4$ and $P_5$) from the neighbouring cluster $C_2$ instead of having to receive one from $P_4$ and $P_5$ as in the full-mesh P2P case. Directionally, a given mixed voice stream is rendered at a **centroid** position which offers the minimal sum of **percentage directional error**. The percentage directional error is the percentage difference between the **actual angular deviations** of all the peer voices rendered and their corresponding **acceptable angular errors** constraints [8]. The **attenuation error** occurs when a given listening peer receives a voice stream that is not attenuated to the exact distance between the listening peer and the corresponding speaking peer. The distance attenuation of the mixed voice stream received by a particular peer $P_j$ from a given cluster $C$ is governed by the minimal distance between $P_j$ and $C$. This minimal distance is the shortest distance from $P_j$ to one of the peers in $C$ which is heard by $P_j$.

### III. Inter-Cluster Routing Algorithms

These two routing algorithms solve the problem of routing voice streams between clusters. These two routing algorithms always adhere to the principle of each peer only receiving one stream from each of the clusters that peer hears.

#### A. Minimal Delay Routing Algorithm

The **Minimal Delay Routing** algorithm finds the shortest path (measured by absolute delay) between any given peer and a cluster which has at least one speaking peers heard by that listening peer. For instance, in Fig. 1, the **Minimal Delay Routing** algorithm routes the voice streams between $P_1$ and $C_2$ along the shortest path starting at $P_1$ which offers the shortest paths between $P_1$ and all the peers in $C_2$ heard by $P_1$. The Minimal Delay Routing Algorithm creates a problem of uneven distribution of inter-cluster voice uploads at the peers. Some peers perform more inter-cluster voice uploads than inter-cluster voice downloads whereas others do not perform any voice uploads. In Table 1, the second and third columns from the left (marked as Case1) displays the inter-cluster uploads and downloads at four of the peers depicted in Fig. 1 when the Minimal Delay Routing algorithm is applied.

#### Table 1. An example of upload and down inter-cluster load distributions in the two routing scenarios

<table>
<thead>
<tr>
<th>Peer Id</th>
<th>Upload Case 1</th>
<th>Download Case 1</th>
<th>Upload Case 2</th>
<th>Download Case 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>4</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>5</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Total</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>4</td>
</tr>
</tbody>
</table>

#### B. Fair Nodal Stress Routing Algorithm

In order to obtain a more even distribution of voice uploads between the peers, we have also implemented the **Fair Nodal Stress Routing** algorithm which finds paths that are not necessarily the shortest in order to minimise the difference between the number of uploads and the number of downloads at each peer. In Fig. 2, the voice streams from $C_2$ to $P_2$ are delivered along the paths starting at $P_5$ instead of at $P_1$ which...
is used in the shortest path routing. Such routing leads to equal number of upload and download at $P_1, P_2, P_4,$ and $P_5$ as shown in the last two columns from the left in Table 1.

IV. **Mathematical Formulation For Cluster Formation**

Let $P_i$ denote a particular peer where $1 \leq i \leq N$ ($N$ denotes the total number of peers in the DVE). We use $C_i$ to denote a particular cluster set up in the Initial Cluster Formation where $1 \leq k \leq N$.

**General Known Variables:**

$$a_{ij} = \begin{cases} 1 & \text{if peer } P_j \text{ can hear peer } P_i \\ 0 & \text{otherwise} \end{cases}$$

Where $j \neq i, 1 \leq i \leq N$

**A. Initial Cluster Formation Formulation**

**Known variables:**

$d_{ij}$ is the distance between peer $P_i$ and peer $P_j$.

$\delta$ denotes the pre-defined pair-wise distance constraint between any given pair of peers in a cluster.

$$e = \begin{cases} 1 & \text{if } d_{ij} \leq \delta \\ 0 & \text{otherwise} \end{cases} \text{ where } j \neq i, 1 \leq i \leq N$$

Because this formulation is decomposable to a peer basis, for clarity, we show the case of the $k$th initial cluster formed around peer $P_i$ in the ensuing mathematical representations.

**Decision variable:**

$$y_j = \begin{cases} 1 & \text{if peer } P_j \text{ is included in the } k \text{th potential cluster} \\ 0 & \text{otherwise} \end{cases}$$

**Objective Function Maximise:**

$$\sum_{j=1}^{N} e_{ij} y_j \forall k$$

The objective of this formulation is to maximise the number of peers enclosed in the $k$th initial cluster.

**Subject to:**

$$e_{ij} y_j y_k \leq \delta \forall j, l \neq i, 1 \leq i \leq N$$

**B. Final Cluster Formation Formulation**

**Known variables:**

$$b^k_{ij} = \begin{cases} 1 & \text{if peer } P_j \text{ is in the } k \text{th potential cluster} \\ 0 & \text{otherwise} \end{cases}$$

$$h^k_{ij} = \begin{cases} 1 & \text{if peer } j \text{ can hear the } k \text{th potential cluster} \\ 0 & \text{otherwise} \end{cases}$$

These two known variables are obtained as the direct results of the Initial Cluster Formation formulation. Please note a peer is said to hear a cluster, if it hears at least one of the peers in that cluster.

**Decision variable:**

$$x^k_j = \begin{cases} 1 & \text{if peer } P_j \text{ is assigned to the } k \text{th final cluster} \\ 0 & \text{otherwise} \end{cases}$$

$$v^k_j = \begin{cases} 1 & \text{if peer } P_j \text{ hears the } k \text{th final cluster} \\ 0 & \text{otherwise} \end{cases}$$

$u_i$ is a non-negative integer variable. $u_i$ equals to the number of peers of the final cluster that peer $P_i$ belongs to.

**Objective Function Minimise:**

$$\sum_{i=1}^{N} u_i + \sum_{i=1}^{N} h^k_{ij} v^k_j$$

In this work, the average access bandwidth consumption per peer is measured by the average number of duplex (send/receive) voice exchange operations per peer. The objective of this formulation is to minimise the total number (both intra-cluster and inter-cluster) of duplex voice exchanges required to support an Immersive Communication Environment (ICE).

**Subject to:**

$$u_j \geq b^k_{ij} x^k_j \sum_{i=1}^{N} b^k_{ij} - \sum_{i=1}^{N} b^k_{ij} x^k_j \forall j, k$$

$$a_{ij} b^k_{ij} \leq h^k_{ij} v^k_j \forall i, j, k$$

$$\sum_{k=1}^{N} b^k_{ij} x^k_j = 1 \forall j$$

V. **Simulations**

In our simulation experiments we use a 5000 nodes Transit-Stub topology [11] to model the Internet topology. Each peer node is assumed to be collocated with a stub router. The topology generator parameters are chosen such that the maximum propagation delay in the shortest path between two nodes is 300ms. We have run our simulations over a peer population of 50, due to the complexity of the final cluster formation formulation.

A. **Average Bandwidth Consumption and Individual Nodal Stress**

In this work, the average access bandwidth consumption per peer is measured by the average number of duplex voice exchange operations per peer. Fig. 3 shows that the average access bandwidth consumption per peer over a range of peer densities from 5 to 30. The three non-linear curves in Fig. 3 correspond to the three pair-wise distance constraints studied, i.e. 5, 10 and 15 meters. The linearly increasing line represents the benchmark case of full-mesh P2P (full mesh uni-cast voice exchanges for every peer).

At the same density, the average access bandwidth consumption is reduced when the pair-wise distance constraints are relaxed from 5 to 10 meters. As discussed in B of Section II, the clustering process achieves bandwidth reduction through replacing the bandwidth-intensive full-mesh (intra-cluster) voice exchanges with inter-cluster voice exchanges. The pair-wise distance constraint controls the sizes of the clusters formed. When imposing the 5 meter pair-wise distance constraint, the small cluster sizes lead to less bandwidth-intensive intra-cluster (full-mesh) voice exchanges but such benefit is far outweighed by the disadvantage that each inter-cluster voice exchange replaces fewer intra-cluster voice exchanges. On the other hand, the extent of reduction from 10 meters to 15 meters is much smaller than that observed from 5 meters to 10 meters. This suggests that when the pair-wise distance constraint is large,
the advantage of having larger clusters (i.e. each inter-cluster voice exchange substituting for more intra-cluster exchanges) is less dominant over the disadvantage of having more intra-cluster voice exchanges within each cluster. Consequently, the choice of pair-wise distance constraint should be a balance between cluster size and the number of clusters formed for maximising access bandwidth reductions. For the scenarios studied in relation to Fig.3, 10 meters can be considered a reasonable choice.

![Fig. 3 Average number of duplex voice exchanges VS peer density](image)

The three curves shown at different pair-wise distance constraints are all non-linear and flatten out at higher peer densities. This trend suggests that the effectiveness of clustering in bandwidth reduction is greater at higher peer densities than lower densities. In the best case scenario, at density of 30 and pair-wise distance constraint of 15 meters, the average bandwidth consumption is reduced by 63% from 30 streams to 11 streams. At higher peer densities, peers are closely packed in the virtual world and a reasonable number of peers can be co-located in one peer, leaving more room for improvement in bandwidth reduction by the clustering process from the full-mesh P2P scenario.

In order to study the individual nodal stress distribution between the peers, we plot the Cumulative Distribution Functions (CDFs) of uploads and downloads at each peer for three interesting scenarios, shown respectively on Figures 4, 5 and 6 (see next page). At the density of 30, the comparison between Figures 4 and 5 shows that when the Minimal Delay Routing Algorithm is implemented, the distribution of individual nodal stresses is much more even or fairer in download than in upload. The distribution of individual nodal stresses in download is unaffected by the choice of routing algorithms as each peer always receives one stream from each of the clusters heard by that peer. Figure 6 shows the distribution of individual nodal stresses in uploads at the density of 30 when the Fair Nodal Stress Routing Algorithm is applied. The comparison between Fig. 5 and Fig. 6 illustrates that the Fair Nodal Stress Routing Algorithm yields a much more even distribution of individual upload stresses than the Minimal Delay Routing Algorithm.

### B. Peer to Peer Delays

Table 2 shows, over different densities and different pair-wise distance constraints, the average (per pairs of communication peers) percentage increase in delay over the full-mesh P2P case when the Minimal Delay Routing Algorithm is applied in conjunction with the two clustering models. The two hop routes found by the Minimal Delay Routing Algorithm for inter-cluster voice exchanges account for the increases in delay over the best-delay scenario of full-mesh P2P. In the worst case scenario, at density of 25 and pair-wise distance constraint of 15 meters, the average percentage increase in delay is 31.51% (actual average delay 179 milliseconds, average full mesh delay 140 millisecond). Table 3 shows the difference between the percentage increase in delay incurred by Minimal Delay Routing and the percentage increase in delay incurred by Fair Nodal Stress Routing. When applying the Fair Nodal Stress Routing Algorithm instead of the Minimal Delay Routing Algorithm, the extra delay penalty incurred is reasonably small. In the worst case of, at density of 25 and pair-wise distance constraint of 15 meters, the application of Fair Nodal Stress Routing incurs an additional 7.62% increase in delay over the full-mesh P2P case, on top of the 26.21% incurred when Minimal Delay Routing is applied.

### C. Peer to Peer Directional Error

We measured the average (per pairs of communication peers) percentage directional error over different peer densities and pair-wise distance constraints. The percentage directional error is the percentage difference between the rendering centroid (see B of Section II) and the exact positions of the speaking peers with respect to the position of the listening peer. In the worst case scenario of peer density of 30 and pair-wise distance set to 15m, 86% of pairs of listening and speaking peers have zero directional errors. For the next ten percentiles (up to 96%), the directional error is below 141%. The next 4 percentiles (to 100%), the error is below 501.33% error. The relevant tables and graphs are omitted due to space limits.

**Table 2.** Delay percentage increase Minimal Delay Routing

<table>
<thead>
<tr>
<th>P/w distance</th>
<th>Density Of 5</th>
<th>Density Of 10</th>
<th>Density Of 15</th>
<th>Density Of 20</th>
<th>Density Of 25</th>
<th>Density Of 30</th>
</tr>
</thead>
<tbody>
<tr>
<td>5 m</td>
<td>3.23 %</td>
<td>2.33 %</td>
<td>11.40 %</td>
<td>11.99 %</td>
<td>19.62 %</td>
<td>19.81 %</td>
</tr>
<tr>
<td>10 m</td>
<td>8.06 %</td>
<td>13.40 %</td>
<td>20.86 %</td>
<td>21.24 %</td>
<td>28.18 %</td>
<td>27.62 %</td>
</tr>
<tr>
<td>15 m</td>
<td>17.03 %</td>
<td>16.26 %</td>
<td>25.81 %</td>
<td>23.67 %</td>
<td>31.51 %</td>
<td>26.21 %</td>
</tr>
</tbody>
</table>

**Table 3.** Extra delay percentage increase Fair Nodal Distribution Routing

<table>
<thead>
<tr>
<th>P/w distance</th>
<th>Density Of 5</th>
<th>Density Of 10</th>
<th>Density Of 15</th>
<th>Density Of 20</th>
<th>Density Of 25</th>
<th>Density Of 30</th>
</tr>
</thead>
<tbody>
<tr>
<td>5 m</td>
<td>0 %</td>
<td>0 %</td>
<td>4.05 %</td>
<td>6.33 %</td>
<td>5.11 %</td>
<td>5.04 %</td>
</tr>
<tr>
<td>10 m</td>
<td>4.32 %</td>
<td>5.67 %</td>
<td>6.02 %</td>
<td>4.99 %</td>
<td>6.33 %</td>
<td>6.63 %</td>
</tr>
<tr>
<td>15 m</td>
<td>4.44 %</td>
<td>5.01 %</td>
<td>7.07 %</td>
<td>5.49 %</td>
<td>5.20 %</td>
<td>7.62 %</td>
</tr>
</tbody>
</table>

### D. Peer to Peer Attenuation Error

The attenuation error measured in our simulations applies to the rendering of inter-cluster streams. Our attenuation error metric is defined as the difference between the chosen attenuation distance for a mixed stream and the exact distance of an individual stream, normalised as a percentage of the hearing range. We measured the Cumulative Distribution
Function of the attenuation errors in the worst case scenario, at peer density of 30 and pair-wise distance of 15 m. In that scenario, the maximal error is 47% of hearing range, and 90% of pairs of peers have error less than 30% of the hearing range. The relevant tables and graphs have been omitted due to the space constraints.

VI. CONCLUSION

In this paper, we proposed a Peer-to-Peer (P2P) architecture to deliver a multi-party immersive voice communication service, called Immersive Communication Environment (ICE) for users accessing a Distributed Virtual Environment (DVE). In comparison to the “brute force” full-mesh P2P approach, real-time voice deliveries in our architecture demands lower access bandwidth at the peers. This bandwidth reduction is brought about by the clustering of pair-wise close peers and the mixing of the voice streams within the same cluster which reduces the number of direct peer to peer voice exchanges. This bandwidth reduction is improved by the relaxing of the pair-wise distance constraint and is larger at larger peer densities. In the best case scenario, the average bandwidth consumption is reduced by 63% from 30 streams to 11 streams. We implement full-mesh uni-cast voice deliveries between the peers within the same cluster in order to ensure high voice quality in delay and rendering for these close-by peers. For the mixed voice streams exchanged between clusters, our architecture minimised the rendering error in those voice streams by choosing an appropriate directional centroid and the appropriate attenuation distance. Our simulation results show that the directional error and attenuation error for most voice streams are reasonably small. To minimise the delay penalties incurred in inter-cluster voice exchanges, we at first implemented the Minimal Delay Routing algorithm which finds the shortest path between peers across clusters. However this Minimal Delay Routing algorithm causes uneven bandwidth consumptions at many peers. The Fair Nodal Stress Routing algorithm is thus implemented to find sub-minimal paths that contribute to a more even distribution of uploads among the peers. Our simulations find that the Fair Nodal Stress Routing algorithm incurs maximally an additional 7.62% increase in delay over the full-mesh P2P case, on top of the 26.21% incurred when Minimal Delay Routing is applied. In comparison to the full-mesh P2P, our P2P architecture delivers real-time immersive voice streams with a good balance between scalability access bandwidth consumptions at the peers, and the rendering and delay qualities of voice streams.

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