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Awareness-based communication management in the MASSIVE systems

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Abstract. The MASSIVE-1 and MASSIVE-2 distributed virtual environment systems are based on an explicit model of user communication requirements known as the spatial model of interaction; this model addresses the general issue of managing communication in large space-based systems such as DVEs. The goals of the spatial model are to guide the distribution and presentation of information in a way which facilitates collaboration between participants (based on observed patterns of interaction in real-world environments) and which is also efficient and appropriate. The MASSIVE-1 system emphasized the spatial model's 'aura' concept as the basis for a distinct shared service in an otherwise wholly unicast peer-to-peer system. This approach was effective for relatively small systems but could not be extended to make general use of multicast communication (to reduce total bandwidth requirements). The MASSIVE-2 system added the concept of 'third-party objects' which support the definition and management of multiple multicast groups for updates and continuous media distribution.

1. Introduction

One of the main challenges for the creators of distributed virtual environments (DVEs) at the present time is the desire to support large and increasing numbers of simultaneous users. For example, in the area of military simulation the intention is to stage full-scale war simulations and training exercises involving 100 000 or more entities. In the civilian arena there is the possibility of making DVE technologies available to consumers as a kind of 'inhabited TV' with many millions of potentially simultaneous users.

As well as requiring a basic level of technological capability and communications infrastructure, these large-scale applications also require an effective mechanism for managing communication and distribution based on each participant's potential 'awareness' or 'interest' within the virtual environment. The term awareness refers here to the availability of information to a participant in a DVE. For example, a participant is aware in the graphical medium of objects which appear in their display and is aware in the audio medium of audio streams which are played out to them. This user-level awareness results from underlying flows of information and media streams within the distribution environment based on whatever networking technologies are available.

Awareness-based communication management (hereafter referred to as 'awareness management') is responsible for mapping between a participant's ideal awareness and the

available communication resources. Awareness management is a key consideration for system scalability because it determines how much information (and how much network traffic, replicated state and rendering overhead) must be handled by each participant's local machine. The use of multicast communication in DVEs can significantly reduce total network bandwidth requirements but it does not address this issue of participant load. Indeed, the use of multicast-based communication may even increase the demands placed on individual participants since it is easier to distribute large amounts of information to large numbers of destinations.

Dealing explicitly with user awareness may also make the system more effective for supporting inter-personal communication and collaboration by supporting perceptual and social factors which are believed to be significant for collaboration in real-world settings. These include: peripheral awareness of 'nearby' activities and targeted production of information (as found in [1]), support for spontaneous interaction (e.g. as motivated [2]) and also focus of attention, balance of power between collaborators and sensitivity to context. At present the MASSIVE systems described in this paper are alone in being based on a sociologically motivated model of general awareness in interaction: the spatial model of interaction, which is reviewed in section 2 of this paper.

Section 3 describes the aura-based distribution architecture of the MASSIVE-1 system and identifies some key limitations. Section 4 then reviews the third-party object extension to the spatial model which addresses these limitations. Section 5 describes key elements of the MASSIVE-2

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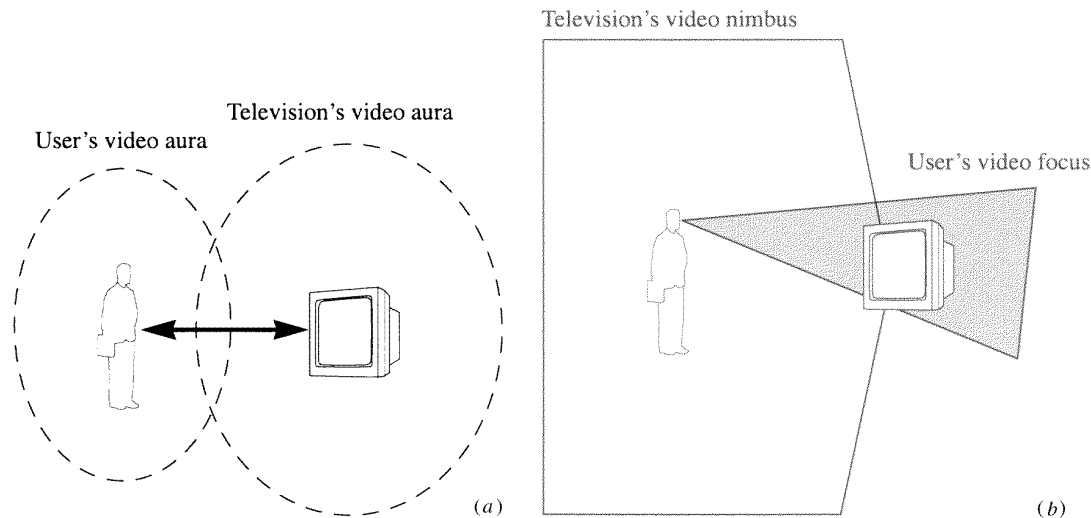


Figure 1. A user encounters a virtual television set in the spatial model; (a) auras (b) focus and nimbus.

system's distribution architecture and explains how it differs from the first system and how it employs third-party objects to manage communication. Section 6 situates this work within the field of DVEs. Section 7 presents a final summary and conclusions.

2. Awareness and the spatial model of interaction (1993)

This section briefly reviews the original spatial model of interaction of Benford and Fahlén [3] which is the basis of the MASSIVE-1 system. Parts of the spatial model have also influenced the DIVE [4] and Virtual Society [5] systems. The model is defined against a background which comprises:

- worlds, which are disjoint spaces within which communication can occur; and
- objects, which are present within worlds.

The key concepts of the spatial model itself are:

- medium, which is a communication type such as audio, visual or text;
- aura, which is an object- and medium-specific subspace in which interaction may occur;
- awareness, which quantifies one object's significance to another object in a particular medium (and which depends on focus and nimbus which are defined below);
- focus, which represents an observing object's interests in a particular medium;
- nimbus, which represents an observed object's wish to be seen (or heard, smelt, etc) in a given medium; and finally
- adapters, which can modify an object's auras, foci and nimbi in order to customize or modify its interaction with other objects.

As a simple example, consider a user encountering a virtual television set. In the spatial model, the television set's picture would be conveyed in a 'video' medium. When the user's video aura overlaps the television's video aura then video communication becomes possible (see

figure 1(a)). This pair of objects then goes on to negotiate mutual levels of awareness. This awareness level can be treated as a desired quality of service from the other object and from the network and might affect the frame-rate or resolution at which the user sees the television image. Awareness is negotiated by combining the observer's focus and the observed's nimbus. In this example, the user has a video focus which matches their visual field of view, while the television set has a video nimbus which points forwards, representing the visibility of the screen relative to the set (see figure 1(b)). Consequently the user is only aware of the video image when (i) they are in front of the television set and (ii) it is within their field of view.

A user in a spatial model-based system can express their desired awareness and thereby control their interaction in three ways:

- by moving about within the virtual world, taking their auras, foci and nimbi with them, e.g. turning to face the television set or moving closer to it;
- by directly modifying the settings of their auras, foci and nimbi, e.g. focusing on the television set; and
- by interacting with adapter objects which implicitly modify their auras, foci and nimbi accordingly, e.g. picking up a virtual telescope which in turn modifies their visual and video auras and foci.

In an implementation of the spatial model a user's local machine could calculate the user's awareness of each known object and use this representation of the user's requirements to guide its interaction with the rest of the system. This is the key focus of the descriptions of MASSIVE-1 and MASSIVE-2 in sections 3 and 5.

3. MASSIVE-1

The previous section has described the spatial model of interaction and the way in which it reasons about awareness based on users' and objects' auras, foci and nimbi, which together specify the desired patterns of communication and interaction within the shared virtual environment. This

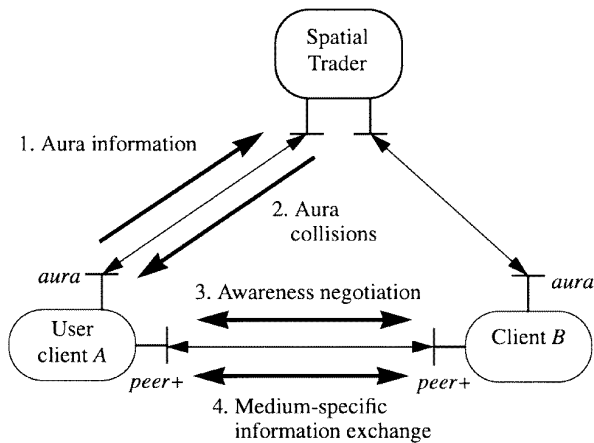


Figure 2. Overview of MASSIVE-1's communication architecture.

section describes MASSIVE-1's distribution architecture and identifies some of its strengths and weaknesses.

The MASSIVE-1 system [6] is a direct implementation of the spatial model of interaction and is designed to support tele-conferencing over wide-area networks. It allows distributed groups of participants to share a virtual universe of linked 3D graphical worlds and to communicate via a flexible combination of real-time audio, text messages and simple graphical gestures. Each medium (text, audio and graphics) is independently controlled by the spatial model of interaction, taking account of aura, focus and nimbus. The calculated awareness levels are used to control the volume of audio streams, the presentation of text and choice of 3D graphical representation (e.g. for level of detail). Users control their desired awareness by moving within and between virtual worlds, by explicitly selecting different settings for aura, focus and nimbus, and by activating (through proximity) adapters such as a conference table and a podium.

Figure 2 shows an overview of the relevant portion of MASSIVE-1's distribution architecture, focusing on a single user, A. Each box is a separate process and each interface is labelled with its type (the unlabelled interfaces have a null type).

In the spatial model and in MASSIVE-1 every user embodiment and every other object has an aura which defines its scope of interest in a particular virtual world. When user A joins a MASSIVE-1 session they begin with a single client process. This contacts a well known spatial trader process and passes to it (and keeps up to date) its world, medium and aura information (1). Many spatial trader processes may exist, each being responsible for a different set of virtual worlds; an inter-trader protocol allows clients to be passed from one spatial trader to another as appropriate. All objects which are in the same world will be referred on to the same spatial trader. The spatial trader uses collision detection techniques to incrementally identify overlapping auras and informs the corresponding clients (2). The objects then establish direct peer connections.

The direct peer connections are used to negotiate awareness values between the two objects which exchange information about focus and nimbus levels (3). They also

exchange medium-specific information appropriate to their current levels of awareness (4); this may include graphical geometries, text messages and pointers to real-time audio streams. In the case of user client processes this information is presented to the user as a 3D graphical view, a simple text interface or real-time audio, as appropriate. When objects move out of aura range the spatial trader notifies them of this and they tear down the direct connection, removing the other object from their local view of the environment (in that medium).

3.1. Network requirements of MASSIVE-1

For DVEs this spatial trading approach has significant advantages over dividing participants only according to world: it allows gradual, natural and visible transitions between groups within the same world; it allows different media to be treated in different ways; it can avoid the need for hard system intervention such as barring access to busy worlds; and it supports flexible control and graceful degradation through interactive or automatic modification of aura. The use of spatial trading also reduces the total network bandwidth requirement for a unicast-based DVE because it ensures that users and objects only communicate while they are in aura range, i.e. while the aura component of the spatial model indicates that interaction is possible and appropriate. If N is the number of simultaneous users and M is the average group size (i.e. the typical size of active groups identified through aura collision) then spatial trading reduces the communication requirements from $O(N^2)$ to $O(NM)$.

However, two significant problems remain with this approach and the MASSIVE-1 system:

- the total bandwidth requirements are still significantly larger than with multicast communication, which could in principle achieve a total bandwidth requirement of $O(N)$; and
- communication is scoped solely according to aura, and does not take account of other application-related limitations on interaction such as boundaries or closed rooms which can be very important in some DVE applications.

To address these problems the third-party object extension to the spatial model, presented in the next section, provides support for context-sensitive interaction in a way that can be exploited to increase scalability. Section 5 then describes the MASSIVE-2 system in which this is prototyped using a complementary multicast-based distribution architecture.

4. Third-party objects

The original spatial model of interaction (described in section 2) reasons about potential awareness between objects in dyadic relationships. Consider now the introduction of a third object, C, as in figure 3. The original spatial model considers every dyadic relationship individually and independently so that the relationship A-B is unaffected by the introduction of C. However, the third-party object, C, may represent some important aspect of

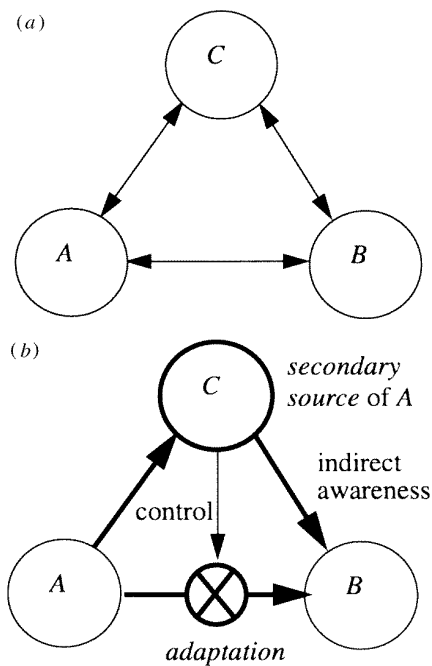


Figure 3. A third-party object and its potential effects; (a) a third-party object, C; (b) adaptation and secondary source effects.

the context in which A and B interact, such as a room or a shared artefact. Involving the third-party object in the awareness negotiation process allows for richer, context-sensitive, patterns of interaction. Third-party objects can also provide necessary cues to allow multiple multicast groups to be used and managed as in MASSIVE-2 (described in section 5). The third-party object extensions to the spatial model were originally presented in [7] and are reviewed here as necessary background for the description of MASSIVE-2 which follows.

Third-party objects can be defined in terms of their effects and their activation, i.e. what they do and when they do it. Third party objects can have two basic effects on awareness which are termed ‘adaptation’ and ‘secondary sourcing’ (see figure 3(b)).

- **Adaptation.** Third-party objects can modify or ‘adapt’ existing awareness relationships, either amplifying or attenuating them. So in figure 3, C can affect A’s awareness of B and B’s awareness of A. For example, C might be a wall which would cut off awareness in both directions.

- **Secondary sourcing.** Third-party objects can introduce new indirect awareness relationships. So in figure 3, C can provide B with information about A even when B has no direct awareness of A. C can also act as a secondary source for a group of objects as well as for a single object, providing group representation services such as group level of detail. For example, C might represent a crowd, which from a distance gives just a general sense of overall noise and movement.

Note that different effects may be applied in each direction and in each medium and that the same third-party object can combine both effects.

The activation of third-party objects is defined in terms of existing direct awareness relationships, specifically those which involve the third-party object itself. So in figure 3 the effect of C on the relationship A–B will depend on the relationships A–C and B–C and the associated awareness levels. Table 1 shows how activation, adaptation and secondary sourcing might be combined in a third-party object to realize a range of useful effects. Note that the roles of A and B are completely reversible and that unspecified effects imply normal direct awareness negotiation.

Third-party objects, as well as having their own particular characteristics, are also first-class objects within the extended spatial model of interaction. Consequently, third-party objects can themselves exploit focus, nimbus and aura to manage their own interaction and operation; they can affect one another, allowing the construction of combined, linked and nested patterns of effects; and, like any object, can be dynamic. For example, in a DVE they might be dynamically introduced into the system, be mobile and change in size and effect over time.

4.1. Communication implications of third-party objects

In MASSIVE-1 and the original spatial model aura collision was a necessary and sufficient pre-requisite for interaction. Equivalently, the only potential interactions which could be ignored were those between objects which were out of aura range. However, with the addition of third party objects there are three situations in which one object cannot possibly be aware of another object (and therefore communication and computation might be avoided). These three situations are:

- when the objects are outside of aura range, as in the original model;
- when the objects are on opposite ‘sides’ (i.e. inside and outside) of an opaque boundary such as the edge of a closed room or building; and
- when one object is within a group level-of-detail (hybrid activated) third party such as a crowd and the other object is outside and has a sufficiently low awareness, so that they are only indirectly aware of the third party’s members.

The first case addresses scoping of interaction in open spaces. The second addresses scoping of interaction based on significant world structure and content. The third affords additional scalability through the introduction of reduced-detail group abstractions. All three are exploited in the MASSIVE-2 prototype which is described in the next section.

5. MASSIVE-2

MASSIVE-2 [7] is a general-purpose DVE system based on the spatial model of interaction and the third-party object concept reviewed above. Like MASSIVE-1, MASSIVE-2 supports user interaction within a shared 3D graphical world via a combination of real-time audio, text messages and simple graphical gestures. A simple 2D map view supplements the normal 3D graphical view. Users are also able to interact with objects in the world by direct

Table 1. Some possible third-party objects.

Effect	Activation	Adaptation	Secondary sourcing
Open cell or region	A within cell and cell within B's area of interest (Aoi)	Cell in B's Aoi: full awareness. Cell outside B's Aoi: no awareness	None
Closed room	A within room ('membership')	A in, B out: no awareness. A and B in: normal awareness	Optionally provide limited information about members
Crowd	A within crowd	A in, B out: A has normal awareness of B, but B has no direct awareness of A	Provides external aggregate view of crowd
LOD region	A within region and B's awareness of region ('hybrid')	A in, B low awareness: no direct awareness. A in, B high awareness: normal awareness	A in, B low awareness: external aggregate or overview (cf crowd)
Panopticon cell	A within cell	A in, B out: A has no awareness of B, but B has full awareness of A	None
Shared artefact	A and B's awareness of artefact ('common focus')	A and B highly aware of C: increase A and B's awareness of each other	None

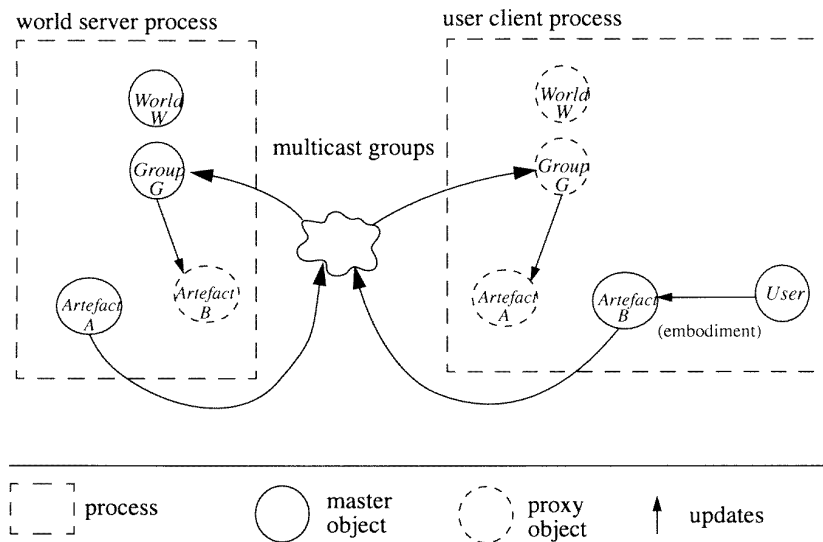


Figure 4. Overview of MASSIVE-2's network and software architecture.

manipulation using the mouse in the 2D or 3D views. All interaction and presentation of information is controlled by the spatial model of interaction with third-party objects; for example, audio volume depends on the combination of user focus, object nimbus and any relevant third-party objects.

5.1. Core system implementation

Unlike MASSIVE-1, MASSIVE-2 is implemented using a proprietary distributed object system with integrated support for remote object proxies and for multicast message sends (mapped onto IP multicasting with a nack-based reliable delivery protocol). Figure 4 shows an overview of the processes and key objects comprising a minimal session, with one world server process (hosting one world and one master artefact, A) and a single user client process (with a single embodiment artefact, B).

The master world object in the world server process represents a single virtual world and provides an initial

point of access. This may be found using the normal (non-spatial) trading facilities of the standard node manager(s) (not shown). Each world is populated by artefact objects which may have representations in one or more media (spatial, text, 2D graphics, 3D graphics and audio). Artefacts are replicated on demand as described in section 5.2. In the figure, artefact A from the world process has been replicated in the user's client process while the user's embodiment, artefact B, has been replicated in the world server process (though possibly only in the spatial medium). Update messages are distributed to artefact replicas via multicast groups and associated group objects as shown. For example, when master artefact B is moved, it sends updates to a specific multicast group; these are received by all of the group objects associated with that multicast group and used to update any replicas of artefact B in other processes.

In MASSIVE-2 spatial trading is carried out locally within each process (by the relevant world object) rather

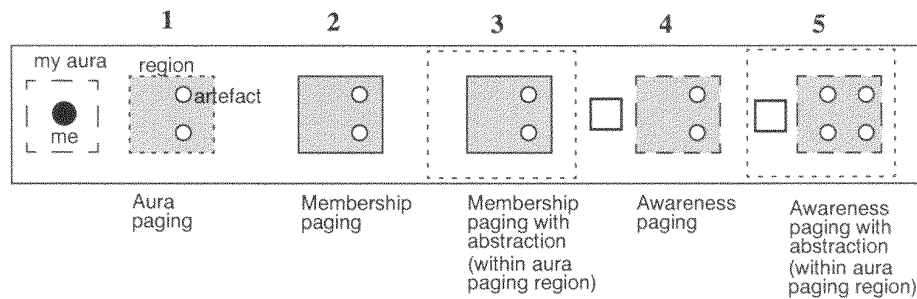


Figure 5. The New Audio Gallery world.

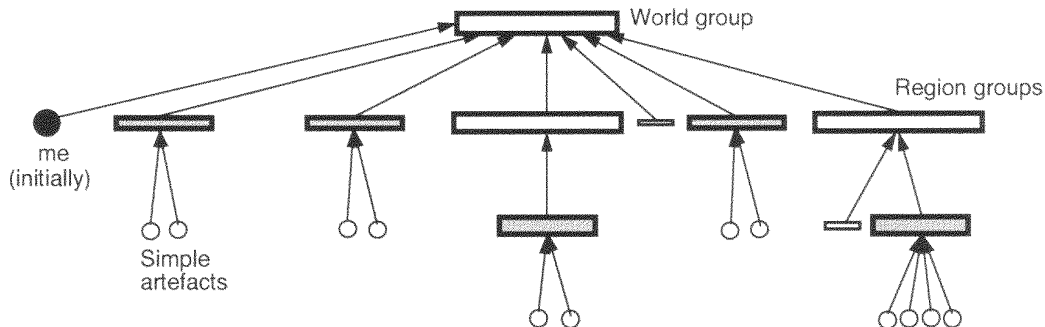


Figure 6. The group and artefact hierarchy of the New Audio Gallery.

than as a centralized service as it was in MASSIVE-1. Each artefact (master or proxy) has a local aura object (not shown in the figure) which is used for spatial trading. Request auras are created locally by observing objects such as the user object in the user client process. These request auras drive local artefact replication as described below, as well as allowing objects to obtain references to virtually local artefacts.

5.2. Realizing third-party objects

Figure 5 shows a schematic view of a world which includes third-party objects (called the 'New Audio Gallery'). This will be used to illustrate the realization and operation of third-party objects in MASSIVE-2. This world includes five different major third-party objects or regions (labelled 1 to 5) plus a further four auxiliary third-party objects which help to illustrate and control the operation of those five.

In MASSIVE-2 any artefact may also be designated a third-party object. This creates a new group object linked to the corresponding artefact plus appropriate multicast group(s) associated with that third-party object. All group objects and artefacts conspire so that each artefact is associated with, and sends updates to, the smallest third-party object which fully contains the artefact. Any artefacts or top-level third parties which do not fall within any subgroup are handled by a top-level 'whole world' group. For example, figure 6 shows the allocation of artefacts to groups which emerges for the situation in figure 5. The arrows indicate the groups to which each artefact (including third-party object artefacts) sends update messages. Note that a third-party object sends only enough

information to its parent group to describe itself and any secondary sourcing it is performing. As artefacts and third-party objects enter and leave the world, move and change size this hierarchy is reconfigured accordingly.

So each artefact, including third-party objects, will send all of its updates to a single group at any one time. However, each process may replicate artefacts (and receive the corresponding updates) for as many groups as is currently required. This replication and multicast-group membership is managed independently by each process according to the local request auras which exist within that process. Replication is managed independently in MASSIVE-2 for each medium of each group (i.e. for each medium of the artefacts currently associated with each third party object). Depending on the type of third-party object replication is managed according to one of three criteria; these are described below and correspond to the three situations in which awareness is not possible in the extended spatial model as noted at the end of section 4.

- **Aura-based paging.** A simple third-party object and the artefacts associated with it are paged in (i.e. replicated within a process) if and only if there is a local request aura which overlaps with the third party. Artefacts are only associated with a third party which fully contains them (spatially) and so if the third party is out of aura range then all of the artefacts associated with it will also be out of aura range and the group can be paged out. This corresponds to the operation of open cells or regions as in NPSNET [8].

- **Membership paging.** A third-party object which is opaque in some medium is only paged in for that medium when there is both an overlapping request aura and the corresponding artefact is actually inside the third party

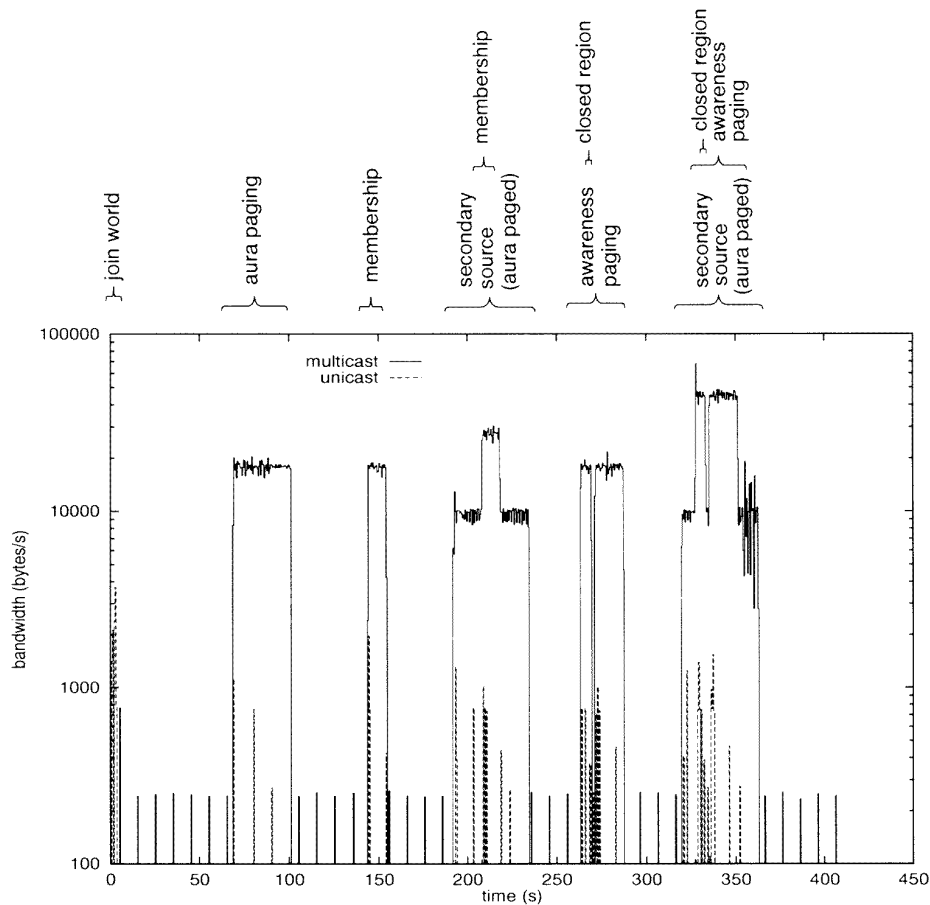


Figure 7. Received multicast bandwidth against time for a tour of the New Audio Gallery.

itself. When an artefact is outside the boundary of this type of third party it cannot be aware of the third party's contents and so the group can be paged out.

- Awareness driven paging. A third-party object may act as a group level of detail abstraction, so that at low awareness levels an observer sees the third party itself while at high awareness an observer sees the individual artefacts within the third party. This form of third party is only paged in when there is an overlapping request aura and the corresponding artefact's awareness of the third party is high enough to be directly aware of its contents.

Figure 7 shows a trace of received multicast traffic against time for a user exploring the New Audio Gallery world from one end to the other at a constant speed. The vast majority of traffic is from the 12 simple artefacts and two secondary sources in the world, each of which is an audio source producing approximately 9 kbytes s^{-1} of multicast audio data.

- Third-party object 1 is an open region which depends on aura-based paging. Around time 70 the user's aura collides with the third party and it is paged in; the two artefacts inside that region are replicated and the corresponding multicast groups are joined.

- Third-party object 2 is a closed room which depends on membership paging. Around time 140 the user enters the room and it is paged in. Note that the room is the same

size as region 1 but is paged in for a much shorter time due to the paging policy used.

- Third-party object 3 is a repeat of the closed room, above, with the addition of audio secondary sourcing, i.e. the room monitors the audio traffic within itself and produces a single mixed audio stream which it sends to its parent group. An additional aura-paged third party has been inserted around the room to restrict the distribution of this secondary sourced audio. When the user approaches this room they initially hear the secondary sourced abstraction. When they then enter the room they hear the artefacts directly (and local presentation of the abstraction is suppressed).

- Third-party object 4 is an awareness-paged level-of-detail (LOD) region. When the user is sufficiently aware of this third-party object it is paged in and they have direct awareness of its members. When they are less aware of the third party it is paged out and they are aware only of the third party itself. There is a small additional third-party object in front of the LOD region which cuts off audio awareness; as the user passes through this their awareness of the LOD region falls and it is paged out.

- Third-party object 5 is a repeat of the LOD region, above, with the addition of secondary sourcing as for case 3. It also contains two additional artefacts.

The use of third-party objects and associated multicast groups in MASSIVE-2 has the following benefits:

- a single virtual world can be divided into a number of appropriate subsections or regions for replication and communication management, allowing larger and more complex virtual worlds to be created;

- this set of multicast groups is shared between the artefacts in a world in a way which is appropriate to the patterns of awareness and communication which are likely to occur in that world (as constrained by the world content which the third-party objects represent);

- the communication management is more flexible and more accurate than using aura alone for environments which include closed subregions and/or group abstractions such as crowds (for example, see [9]).

6. Related work

Not all DVE systems explicitly address awareness management: some deal only with undivided, fully replicated, worlds. Of those that do have some form of awareness management most tacitly or explicitly adopt a single pragmatic approach, often based on a single motivating application area. No other systems at present address support for social issues in interaction through an awareness-like facility.

An early version of DIVE [4] used the spatial model aura concept to control audio communication and to control elements of application behaviour, however, the basic spatial and graphical world was fully replicated. The Virtual Society project [5] has a client-server based architecture which employs auras to scope interaction. This may be compared to MASSIVE-1's use of aura, though it has additional elaborations to restrict the number of active peers at any time in view of the very limited (modem) bandwidths available to domestic users. However, neither of these systems include focus, nimbus or explicit awareness.

A number of multicast-based systems have significant elements in common with MASSIVE-2. NPSNET [8] tiles the world with hexagonal cells, each with its own multicast group. Each observer has their own area of interest (AoI)—equivalent to an aura in the spatial model—which identifies the cells which are potentially of interest to them. The approach adopted by Broll [10] divides the world into a hierarchy of cells or zones of different sizes and shapes, each having its own communications infrastructure (e.g. multicast groups). Zones are disjoint, and when external to a cell the participant may see an (optional) external representation of the cells' contents (cf abstractions). In a slightly different style the Spline system [11] composes the world from 'locales' which may have an arbitrary shape and may be linked together by arbitrary transformations. Interaction and awareness is limited to the current locale and its immediate neighbours.

The cells of NPSNET, the zones of Broll's work and the locales of Spline perform the same structuring function as third-party objects in MASSIVE-2. In all of these systems (MASSIVE-2 included) multicast groups are associated with these structuring facilities rather than with individual artefacts in order to reduce the number of multicast groups required (with their associated management, OS kernel

and network routing resource requirements). However, none of these other systems deals explicitly with awareness as a first-class concept and so none of them can define or exploit individual third-party effects when managing communication and replication.

RING [12] scopes interaction and communication according to potential visibility in densely occluded environments (e.g. within buildings). This is based on a client-server system with distributed servers performing message filtering and visibility calculation. This is one (medium and application-specific) area in which the accuracy of MASSIVE-2 is still limited. This might be tackled through a more explicit consideration of the role and effects of the medium itself.

7. Summary and conclusions

This paper has described key distribution aspects of the MASSIVE-1 and MASSIVE-2 systems. These are currently unique in being based on an explicit model of user communication requirements, in this case the spatial model of interaction. The MASSIVE systems and the spatial model address the general issue of managing communication in large space-based systems such as DVEs. The goals of both are to manage the distribution and presentation of information in a way which facilitates collaboration between participants (based on observed patterns of interaction in real world environments) and which is also efficient and appropriate.

The MASSIVE-1 system emphasizes the spatial model's 'aura' concept as the basis for a distinct shared service in an otherwise wholly peer-to-peer system. This is based on a shared 'spatial trading' service which brokers between auras from different processes. Detailed awareness negotiation and other communication is performed over direct inter-process connections after aura collision has occurred. This approach was effective for relatively small systems but could not be extended to make general use of multicast communication (to reduce total bandwidth requirements) and did not take account of other application-related limitations on communication such as the presence of closed rooms or boundaries within the virtual world.

To address these problems the third-party object extension to the spatial model was proposed to provide socially motivated support for context-sensitive interaction in a way that can be exploited to increase scalability. This is used in the MASSIVE-2 system to support the definition and management of multiple multicast groups for updates and continuous media distribution.

This paper advocates the use of an explicit computational model of user communication requirements, expressed in terms of awareness. The spatial model of interaction is one such model, but many others are possible. This computational model of awareness provides the basis for user- and application-specific management of communication. By making awareness explicit in this way the system can be made more scalable (by managing communication in a more flexible and accurate manner) and important social factors in interaction and collaboration can

be supported, such as peripheral awareness and the tailored projection of information. Making awareness explicit also allows awareness-related meta-information to be made available to the user (e.g. who they can see and hear, who can see and hear them); this may be particularly important with radical forms of focus, nimbus or third-party effects.

The MASSIVE-1 and MASSIVE-2 systems show that such an approach can be applicable to both multicast and unicast-based implementations.

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