

On Consistency and Network Latency in Distributed Interactive Applications: A Survey – Part II

Authors:

Declan Delaney

Tomas Ward

Seamus McLoone

Affiliations:

Department of Electronic Engineering

National University of Ireland, Maynooth

Maynooth

Co. Kildare

Ireland

Corresponding Author details:

Declan Delaney

Via Matteotti 9,

20097 San Donato Milanese,

Italy

Email: drd@eircom.net

Tel: 0039 02 55600325 or 0039 02 52061478

On Consistency and Network Latency in Distributed Interactive Applications: A Survey – Part II

Declan Delaney, Tomas Ward, Seamus McLoone

Abstract – This paper is the second part of a two part paper that documents a detailed survey of the research carried out on consistency and latency in distributed interactive applications (DIAs) in recent decades. Part I reviewed the terminology associated with DIAs and offered definitions for consistency and latency. A classification for consistency maintenance mechanisms was given and various mechanisms belonging to the first of three categories, time management, were described. Here, in the second part of the paper, the remaining two categories of mechanisms are examined – information management (such as predictive contract techniques, relevance filtering, packet bundling) and system architecture (such as QoS and protocols).

I. INTRODUCTION

Despite increased processing power at participating nodes and the availability of greater communications bandwidth, the fundamental limitation to the deployment of Distributed Interactive Applications (DIAs) is the problem of maintaining a consistent worldview in the presence of latency and jitter. In part one of this paper, the link between consistency and a number of aspects of DIAs such as temporal and spatial synchronisation, causality or ordering and concurrency was explored. The link with responsiveness and fidelity was also explored, in that poor consistency can lead to problems of fidelity, and fidelity is often sacrificed to maintain both consistency and responsiveness. To avoid inconsistencies such as divergence, causality violation or expectation violation, various techniques and methods have been proposed and implemented over the years. We refer to any element employed to ensure a sufficient, uniform dynamic shared state for all participants in a DIA as a consistency maintenance mechanism.

Three categories of these mechanisms were identified and the first of these, time management techniques, was explored in part one of the paper (Delaney, Ward and McLoone 2006). Here, we explore the remaining two categories – information management and system architecture. It should be noted that the techniques are not mutually exclusive and the DIA designer can mix techniques across categories to suit each particular application. The paper ends with some concluding remarks.

II. CONSISTENCY MAINTENANCE MECHANISMS

Information Management Techniques

Predictive Contract Agreement Mechanisms – Dead Reckoning

Predictive contract agreement mechanisms are optimistic consistency maintenance mechanisms that operate by employing a form of controlled inconsistency (Zeigler, Cho, Lee, Cho and Sarjoughian 1999). All participants agree on a prediction algorithm, an associated threshold error and a convergence algorithm. The threshold error reflects the amount of inconsistency that will be permitted to occur between the true state and the predicted state. When this error is exceeded, the inconsistent state is corrected by transmitting current state information to all other participants who must subsequently converge to this updated state. Predictive contract agreement mechanisms reduce the amount of network traffic and therefore reduce the network latency.

In DIAs where much of the state information relates to the movement of entities, a polynomial predictor algorithm can be employed to reduce the amount of packets transmitted. The Distributed Interactive Simulation (DIS) standard defines a dead reckoning protocol to achieve this. This protocol consists of a polynomial prediction algorithm and a convergence algorithm (IEEE 1993; IEEE 1995). Dead reckoning is a bandwidth saving mechanism and compensates for variable communication latency (Lin and Schab 1994; Capin, Emerald and Thalmann 1999; Baughman and Levine 2001). A synchronization message must be transmitted to adjust for inconsistencies that can result if dead reckoning is employed in the long term (Lui 2001).

Dead reckoning has been described, analyzed and modeled by a number of authors. It has been modeled as a Markov chain by Kwang-Hyun and Jong-Sung (2001) and as hybrid automata in (Ozutam and Oguztuzun 1999), where it is called the *players-and-ghosts* paradigm (Blau, Hughes, Moshell and Lisle 1992). Durbach and Fourneau (1998) studied the influence of dead reckoning on the network performance and on the response time. They constructed a model of the inter-arrival times of packets on a real network and then represented the network as a Markov chain. They claim that their model of network packets is more accurate than those based on Poisson models.

The concept of dead reckoning has been extended to entity attribute extrapolation within the High Level Architecture (HLA) framework (Lin, Blair and Woodyard 1997; IEEE 2000). It has also been enhanced by combining it with a priority round robin scheduling mechanism (Faisstnauer, Schmalstieg and Purgathofer 2000) and by employing a Kalman filtering approach to complex entities such as the human body (Capin, Pandzic, Thalmann, Magnenat and Thalmann 1997). Dead reckoning has been used to predict the occurrence of deterministic events. These events can then be transmitted to other users in advance and thus improve the consistency (Roberts, Strassner, Worthington and Sharkey 1999; Krumm-Heller and Taylor 2000).

Variations on the standard DIS dead reckoning algorithms have been proposed. Singhal and Cheriton (1995) described a Position History-Based Dead Reckoning protocol. This is a hybrid technique that employs a first order polynomial estimator for very low and very high acceleration. Otherwise second order parabolic estimation, which uses the three most recent packet updates, is employed. Adaptive dead reckoning algorithms, based on variable threshold or variable prediction algorithm, have been described by various authors (Singhal 1996; Bahadir and Halit 1999; Cai, Lee and Chen 1999; Lee, Cai, Turner and Chen 2000). The dead reckoning protocol has also been customized to account for entity-specific characteristics (Bassiouni, Chiu, Loper, Garnsey and Williams 1998).

Duncan and Gračanin (2003) proposed a pre-reckoning algorithm which complements the dead reckoning approach. If a sudden change in movement is detected, such as a ninety degree turn, then an

update packet is generated immediately instead of waiting for the dead reckoning prediction threshold to be exceeded. Group dead reckoning (Das, Singh, Mitchell, Kumar and McGee 1997) aims to prevent continuous flow of positional messages as a user moves through the environment of the DIA. It employs an interval-based scheme, with entities sending positions to a central controller at discrete intervals only if their position has changed. This controller then forwards positional data to other users as needed.

Delaney et al. proposed a hybrid predictive contract technique, which chooses either a short-term deterministic dead reckoning model or one of a family of long-term statistically-based models (Delaney, Ward and Mc Loone 2003b; Delaney, Ward and Mc Loone 2003a). This results in a more accurate representation of the entity's movement and a consequent reduction in the number of packets that must be communicated to track that movement remotely.

Relevance Filtering

Relevance Filtering is based on the idea that most users of the DIA are only interested in a subset of the large volume of data available. It operates by analysing the semantics of packets on transmission or reception and selecting only those which match a certain criterion (Bassiouni, Williams and Loper 1991; Bassiouni, Chiu, Loper, Garnsey and Williams 1997). It is often used in conjunction with multicast protocols, so that a single source node simultaneously transmits to multiple destination nodes. Relevance filtering is also referred to as interest management, data distribution management, data flow management, data filtering and data subscription (Singhal 1996; Morse, Bic and Dillencourt 2000).

The objective of relevance filtering is to control the flow of data. Probably the most general model of data flow is the aura-nimbus model proposed by Benford and Fahlén (1992; Benford and Fahlén 1993). The essential components of the model are the medium, the aura, the focus and the nimbus (Greenhalgh and Benford 1997). The *medium* is a communication type such as audio, visual or text. The *aura* is an object- and medium-specific sub-space in which interaction (communication) may occur.

For example communication might be restricted to audio only; hence an audio aura. Entities must have intersecting auras to communicate. Within the aura different levels of awareness can be established. To achieve this each entity is given a focus and a nimbus. The focus defines the sphere of influence of the entity; the nimbus defines the sphere of interest. For example, if the nimbus of entity 1 intersects the focus of entity 2, then entity 1 has awareness of entity 2 and entity 2 can thus share state information with it. The nimbus and focus spheres can be defined by characteristics such as sensor capability, entity type, spatial distance, location and social awareness. The spatial model was extended by the introduction of third party objects, which are independent objects in a virtual world that can perform various awareness adaptations and aggregations (Benford, Greenhalgh and Lloyd 1997a; Benford and Greenhalgh 1997b). These objects can adapt the level of awareness between DIA users as a function of the task being performed and they allow the application of filters to reduce level-of-detail or the aggregation of data. Aggregation (e.g. creating a new group object from individual objects) is also referred to as granularity in (Roberts 2004). The objective of third party objects is to facilitate construction of the DIA and improve scalability in interactive environments, while maintaining consistency. Most relevance filtering techniques can be related to this model, with refinements to deal with the scalability issue. However, if this model is implemented as described, it doesn't scale to large numbers of active entities (Benford et al. 1997b), as all entities need to be examined for intersecting aura, nimbi and foci and thus the consistency of the DIA is gradually lost.

In developing a taxonomy of relevance filtering techniques, Morse et al. (2000) identified two overall elements in every relevance filtering technique:

1. An implementation architecture for performing the filtering;
2. A method for expressing interest.

To express interest, relevance filtering employs a concept known as interest expressions (Morse et al. 2000). These define the data the entity is interested in receiving using a specific syntax. Processes

accept subscriptions from user entities, evaluate interest expressions and use them to filter messages in accordance with user needs expressed in the user subscription. Dedicated processes called Interest Managers may be used for achieving this. The filtering process may be viewed as being either extrinsic or intrinsic. When the data is filtered based on examination of the header properties of the transmitted packets, such as the packet's source/destination addresses, it is referred to as *extrinsic filtering*. When the filtering is performed by analysing the application-specific contents of the packet it is called intrinsic filtering. Extrinsic filtering is quicker to perform but less precise than *intrinsic filtering*.

Various selection criteria have been employed in interest expressions to define the data of interest:

1. occlusion or culling, which might exclude all information out of visual or audio range (Funkhouser 1995; Roehle 1997);
2. some physical attribute such as spatial proximity, location, social awareness, sensor type, temperature or radio transmission frequency, or entity-type (Bassiouni et al. 1997; Morse et al. 2000);

There are various filtering implementation architectures. In the RING system, all entity updates are sent to a central server and the server only forwards updates to those nodes with entities that are visible to each other (Funkhouser 1995). Similar to this approach is *Area of Interest* (AOI) data management (Macedonia, Zyda, Pratt, Barham and Zeswitz 1994). In MASSIVE the AOI corresponds to the aura (Greenhalgh and Benford 1995). AOI data management is an intrinsic filtering scheme and it requires all nodes to relay entity state data to one or more central managers called Area of Interest Managers (AOIM) or subscription managers. Nodes must also inform the managers of the data they are interested in receiving. The managers then decide what data to forward to each node based on some selection criteria such as distance (Bassiouni et al. 1997; Anthes, Heinzlreiter and Volkert 2004). Unicast communication is used because AOI produces a customized stream of data for each node.

Another implementation architecture employs multicast communication. In this case data is transmitted to multicast groups and nodes must join or leave a group to start or stop receiving data from that multicast group. It is important to partition the data efficiently among the multicast groups to avoid nodes having to join several different groups, each containing a small quantity of essential data. In addition the number of join/leave operations must be minimized as these increase network traffic, consume computing resources and hence cause latency to increase. Data may be partitioned so that it is associated with an area of the virtual environment or with an entity (Barrus, Waters and Anderson 1996b; Rak and Van Hook 1996; Zou, Ammar and Diot 2001). In *entity-based filtering*, each entity is allocated a different multicast network address. An entity multicasts its state information to another entity if their auras intersect and if it has previously subscribed to receive information from it. An example of this kind of filtering is the work by Lee et al. (2000). *Grid-based filtering* divides the DIA into cells and each cell is assigned a multicast network address (Macedonia, Zyda, Pratt, Brutzman and Barham 1995; Capps and Teller 1997). A group of participants is associated with each grid cell. A participant joins the multicast group associated with each cell its AOI intersects (Proximity Detection) (Abrams, Watsen and Zyda 1998). Thus, multicast groups change as participants move around the DIA and both the filtering efficiency and management are dependent on the grid size (Morse et al. 2000). The shape of the regions or cells can be rectangular as in the ModSAF system (Russo, Shuette, Smith and McGuire 1995; Rak et al. 1996). To reduce the number of grid cell meeting points to three, the cells in NPSNET are hexagonal in shape (Macedonia et al. 1995). In Spline the cells are called Locales and they can be any shape or size, so that the cells can be built around the structure of the virtual environment (Barrus, Waters and Anderson 1996a; Barrus et al. 1996b). The grid-based and entity-based filtering approach can be combined to achieve a finer partitioning of the data as in the three-tiered management employed in (Abrams et al. 1998).

The use of static cell sizes will break down if all entities are located in a sufficiently small area of the DIA. One approach to solving this is to dynamically modify the size of the regions as in (Abrams et al.

1998). Each region receives low-fidelity information about entities such as position, speed and orientation. This information can then be used to gather more high-fidelity information. Another approach to solving this problem is to dynamically adapt the AOI as the density of objects in the AOI either increases or decreases (de Oliveira and Georganas 2003). Robinson et al. (2001) shift the boundaries between the areas of interest so that users are balanced among areas. Han et al. (2000) proposed a scalable interest management technique based on spatial distance and user interests. Their technique also deals with crowd clustering in a specific area of the DIA environment and shows a significant improvement in scalability performance of large-scale DIAs compared to existing approaches.

Another scalable interest management technique is used in MASSIVE-2 (Benford et al. 1997b; Benford, Reynard, Greenhalgh, Snowdon and Bullock 2000). Here third party objects are employed to construct the spatial structure of the virtual world. Hence there is a dynamic hierarchy of group objects which maps directly onto the virtual world. Each of these groups has a multicast address and entities join/leave different groups as they move about the virtual environment. In addition the awareness level can be adjusted to match the task being performed by each group.

Relevance filtering software is normally deployed on a central server that relays relevant data to participating nodes based on a set of criteria and knowledge of the state of entities at each node in the DIA. However, if a central server is not employed, there is the paradox that in order for entities to know when not to transmit updates to each other, they must continuously update each other on their current state (Makbily, Gotsman and Bar-Yehuda 1999). To reduce the number of update packets in this case, Makbily et al. (1999) proposed a filtering approach based on update-free regions for pairs of entities. These regions are mutually irrelevant regions in user-parameter space, when interaction between the two users is not possible. This idea exploits the visual relevance relationship (based on the criteria of proximity, visibility and direction) between users. It builds on the concept of a Potentially Visible Set (PVS) (Airey, Rohlf and Frederick P. Brooks 1990). A similar, though more robust

implementation called Frontier Sets was proposed by Steed and Angus (2004; Steed and Angus 2005). The objective in both these proposals is to increase the scalability of the DIA by reducing the quantity of update packets; hence network latency is reduced and consistency can be maintained despite additional data throughput. Bassiouni et al. (1998) also examined the issue of decentralized filtering in the form of gateway servers, a kind of hybrid centralized/peer-to-peer system, referring to the resulting inconsistencies as filtering errors. They proposed, designed and evaluated a number of reliable filtering methods such as gateway dead reckoning, periodic broadcast and reachability range. They found that each of the methods they proposed resulted in additional network traffic, with a trade-off between network traffic and global consistency of the DIA.

One problem that limits the implementation of relevance filtering is the limited number of IP multicast addresses available in Internet Protocol version 4 (IPv4) (de Oliveira et al. 2003). This problem should be solved when Internet Protocol version 6 (IPv6) becomes widely deployed, whenever that may be. Morse et al. (2000) noted the restrictions imposed by multicast hardware and the overhead involved in configuring and reconfiguring groups and suggest that in some cases this additional processing may add to the latency problem.

Cai et al. (1999) employed relevance filtering concepts to determine error thresholds for dead reckoning algorithms. They established four threshold levels based on an entity's AOI and its sensitivity region. When the sensitivity region of one entity intersects the AOI of another entity a collision is almost certain to occur. Their experiments showed a reduction in transmitted packets without a reduction in extrapolation accuracy.

The performance and reliability of relevance filtering has been comprehensively documented by Bassiouni et al. (1997). They evaluated different design alternatives of filtering at transmission and filtering at reception for a spatial distance filtering criteria. Filtering at transmission provides the greatest bandwidth saving, whereas filtering at reception only serves to filter incoming messages at a gateway node for a local network. They demonstrated a significant reduction in transmitted packets for

various AOI distance values. The emphasis of their work was very much on bandwidth usage. They did not address the issue of latency. The issue of consistency was addressed by examining the filtering errors introduced when data that should not have been filtered is filtered. To combat this they make a number of proposals for reliable filtering schemes. Interested readers are referred to the paper for more details (Bassiouni et al. 1997).

Data Compression

Although data compression has the same goal as relevance filtering, they are quite distinct mechanisms (Singhal 1996). Data compression is a technique for the efficient storage and transmission of data (Bassiouni 1985; Bassiouni and Mukherjee 1990). In DIAs, the objective of compression is to reduce the size of the transmitted packets. Packets should be compressed at the transmitting node and then decompressed at the receiving node.

There are two main categories of compression techniques (Singhal and Zyda 1999):

1. **Lossless compression:** reduces the amount of data by changing the encoding format for the packet while ensuring that there is no loss in information;
2. **Lossy compression:** may eliminate some of the redundant or irrelevant data from the packet. Dead reckoning may be viewed as a lossy compression as only a sampled version of the entity's movement is transmitted to other nodes.

Each of these types of compression may involve internal or external compression. *External compression* operates on the data in the current packet and previously transmitted packets. *Internal compression* operates on the data in the current packet only. For internal compression to be useful the following inequality must be true:

$$\frac{P_L - P'_L}{B} \geq 2T_c \quad (6)$$

where

P_L is the original message size;

P'_L is the message size after compression;

B is the bandwidth;

$2T_c$ is the time taken to execute the compression/decompression algorithms.

The type of compression employed is generally dependent on the data being compressed and hence on the application domain. However, PICA (Protocol Independent Compression Algorithm) is an application-independent external compression technique that reduces the bit rate in DIAs (Bassiouni et al. 1997). It operates by sending only the byte difference between the current state of an entity and a reference state.

Interestingly, most modern modems compress outgoing data to optimise bandwidth usage, but this tends to increase latency as the modem needs a minimum amount of data before it can compress and send data. In other words, the inequality in equation 6 is violated. There is a hardware timeout if no further data is forthcoming (Cheshire 1996). Manufacturers such as 3Com and Motorola have developed modems for entertainment DIAs that send data packets instantaneously, thus avoiding the latency associated with data buffering at the network layer and illustrating the importance of application layer compression for DIAs.

Packet Bundling

Packet Bundling or *aggregation* is another data management technique, motivated by the fact that networks can only handle a limited number of packets per unit time (Hook, D., Newton and Fusco 1994). The idea is to reduce the number of packets transmitted, in contrast to packet compression, which seeks to reduce the size of each transmitted packet. It involves assembling a number of

individual packets into a larger data unit and transmitting this new unit as a single packet. Most routers, bridges and gateways can only process a fixed number of packets per unit time. Thus, by grouping a number of packets together, the network can handle more data per unit time. There is also a reduction in the amount of data transmitted, as a single packet header/trailer replaces the headers/trailers of a number of individual packets.

The size of the bundled packet is determined by the network, and is usually limited to the maximum Ethernet packet size of 1500 bytes. Thus, to transmit a large packet the network uses a process known as fragmentation. Fragmentation introduces the additional issues of fragmentation strategy and reconstruction strategy, introducing additional processing overhead (Tanenbaum 1996). Bundling also introduces latency because the transmission time of some packets will be delayed during the bundling process so that other packets can be included. This may make it more difficult to maintain DIA state consistency, although packets containing time critical information do not have to be bundled. There is also a processing overhead involved in assembling and segmenting the packets at both the source and the destination. As a result there is a trade-off between bandwidth, packet size and latency. This trade-off can be managed by using a timeout policy (which means that there is an upper delay limit), a quorum-based policy (a minimum number of packets to bundle) or a combination of both (Singhal et al. 1999).

As part of their overview of the main techniques used to reduce bandwidth usage in entity-based virtual simulations, Bassiouni et al. (1997) investigated packet bundling in ATM-based DIS environments. They concluded that bundling under ATM is not rewarding because of the additional delay introduced by the segmentation (i.e. fragmentation) and assembly of packets. ATM cells are 48bytes in size. They also found that the rate of increase in ATM delay with bundled packet size is greater than the rate of increase in time needed to transmit the bundle.

Liang et al. (1999) proposed and studied the performance of two packet bundling techniques employing single and multiple priority queues. Their approach defines four levels of priority according

to the nature of the data – time critical data is given high priority, heart beat data (periodic messages sent by entities to indicate they still exist) is given low priority. Each priority also has an associated timeout; high priority data has a low timeout. With multiple priority queue, bundles with low priority packets are allowed to be larger than bundles with high priority packets. Bundles with high priority packets will always be transmitted first. In the single priority queue, all packets are queued in order of priority. Bundles are generated by taking packets from the queue until either the maximum packet size is reached or a timeout occurs for one of the packets in the bundle. In this case a balance must be reached between bandwidth, bundle size and timely delivery. Their simulation results show a reduction in the average packet transmission rate and average bandwidth requirement, but an increase in the overall latency time.

System Architecture Techniques

DIA's require sufficient consistency to make interaction appear realistic across large distances. However, network latency makes it difficult to satisfy this requirement. Techniques for reducing the quantity of information that must be communicated across the network aim to reduce the impact of latency. Time management techniques seek to synchronize data so that users share the same view of the application state. For collaborative interaction, this synchronisation is time critical and so the effects of network latency must be overcome. The implementation of these techniques exploits a number of concepts, technologies and approaches that aim to improve the efficiency of processing and disseminating data among participating nodes of the DIA and that therefore impact the consistency of the application and the effects of network latency.

Network architecture

A DIA consists of a number of computers that are interconnected and may be geographically dispersed. How these computers are connected affects the management of data and hence the ability to

maintain consistency and reduce the effects of network latency. There are two basic architectural topologies: client-server (c-s) and peer-to-peer (p2p).

In p2p architectures information is transmitted directly between participants (Frécon and Stenius 1998; Balikhina, Ball and Duce 2002; McGregor, Kapolka, Zyda and Brutzman 2003). Each participant maintains a replicated version of the distributed world and consequently consistency is difficult to maintain (Dourish 1995). However, this architecture facilitates local responsiveness and minimises consistency problems associated with concurrency. Examples of p2p architectures include DIS (IEEE 1993), MASSIVE (Greenhalgh et al. 1995; Greenhalgh 1999), DIVE (Carlsson and Hagsand 1993), Mr Toolkit (Shaw, Green, Liang and Sun 1993) and NPSNET (Macedonia et al. 1994).

In contrast a c-s architecture provides a central authority to which all participants connect. The server maintains the definitive state of all entities and controls distribution of information between participants. The client nodes are responsible for rendering information to the participant and updating the server with changes. This makes it easier to maintain consistency, but with reduced responsiveness due to network latency. Consistency becomes more difficult to maintain as the application scales up and the quantity of data to be managed increases. This is because the server acts as a bottleneck. In addition the operation of the entire DIA hinges on a single server. Examples of c-s architectures include RING (Funkhouser 1995), VLNET (Pandzic, Lee, Thalmann, Capin and Thalmann 1997) and NetEffect (Das et al. 1997). In BrickNet the virtual world database is split over a number of nodes, with a server acting as broker to keep track of what part of the world is being maintained by each node and relaying sufficient information to maintain the level of consistency requested by each node (Singh, Serra, Png and Ng 1994).

The p2p and c-s architectures may be combined to produce hybrid architectures. Examples include SPLINE (Waters, Anderson, Barrus, Brogan, Casey et al. 1997a), Community Place (Lea, Honda, Matsuda and Matsuda 1997) and PaRADE (Roberts, Sharkey and Sandoz 1995). Multiple servers with coordinated data flow between them can provide scalability and redundancy. The servers themselves

are connected using a p2p architecture and participants connect to only one server. The servers then coordinate their activities to relay information between interested participants. Multiple server system architectures introduce additional latency to the system as well as having to perform more processing of the data received from participants and other servers (Singhal et al. 1999). A hybrid network topology to facilitate tightly coupled collaboration was proposed by Anthes et al. (2004). They defined an entity hierarchy consisting of three levels – clients, domains and clusters. Each level in the hierarchy is responsible for certain tasks. Domains can be split or merged as the number of clients increases or decreases. To facilitate closely-coupled collaboration temporary p2p connections are established between clients by their domain server; prediction based on a spherical AOI is used to decide the necessity for a p2p connection. State updates use a hierarchical message distribution scheme, beginning with clients, then domains and finally clusters, which then multicast the message to other domain servers.

Communication Protocols

DIAs rely on the transfer of data between participating nodes in the shortest time possible to ensure a sufficiently consistent world view for all participants. Regardless of the network architecture, this data must be communicated unambiguously between nodes. A protocol is an agreement between the communicating parties (nodes) on how communication is to proceed (Tanenbaum 1996). This agreement can be taken at different layers in the ISO OSI Reference Model. Normally, protocols for DIAs are defined at either the application layer or the transport layer. The most commonly supported network layer protocol is IP (Internet Protocol).

The most common transport layer protocols are the Transport Control Protocol (TCP), which guarantees reliable transmission across a distributed environment, and the User Datagram Protocol (UDP), which operates on a best-effort basis (Tanenbaum 1996; Choukair and Retailleau 2000a). The impact of network latency on the DIA when employing TCP and UDP depends on the type of interaction occurring in the DIA. For short-term interactions, when the amount of information is small

and it needs to be transmitted on an irregular basis, UDP is preferred over TCP; for long-term interactions, when data needs to be sent regularly or a large amount of data needs to be transmitted, then TCP is to be preferred. There is thus a trade-off between the quantity of data to be transmitted and the regularity of transmission. This is a consequence of the overhead involved in setting up and destroying network connections.

To overcome the unreliability of UDP, DIS (IEEE 1993) and SPLINE (Barrus et al. 1996a) send messages with complete object state. In this way even if some messages are lost, consistency can be restored when the next message arrives. A new protocol, called the Stream Control Transmission Protocol (SCTP), is similar to TCP as it provides reliable full-duplex connection (Caro, Iyengar, Amer, Ladha, Heinz et al. 2003). However in addition it offers new delivery options that suit multimedia applications such as *multistreaming*, allowing independent delivery among data streams, *multihoming*, allowing end points of a single association to have multiple IP addresses and *partial reliability*, allowing each message to be assigned a delivery reliability level.

TCP and UDP are examples of IP *unicast* protocols, sending packets to one destination node at a time. DIAs, however, may potentially have hundreds of thousands of simultaneous participating nodes. If each participant were to transmit information directly to every other participant, the interconnecting networks would quickly become congested and it would be impossible to maintain a consistent application with increased scalability for the sending node. To resolve this inefficient communication, IP *multicast* protocols are employed (Deering 1989; Deering and Cheriton 1990). IP Multicast is a network layer protocol that provides simultaneous unreliable transmission to multiple destination nodes. In DIAs, multicast is used extensively in relevance filtering, with each group being assigned a unique multicast address. It is also used whenever messages need to be sent to multiple nodes efficiently to increase the scalability of the DIA (Macedonia et al. 1995). A number of disadvantages of IP Multicast have been documented: it is difficult to implement efficiently on a point-to-point medium; many Internet routers are not multicast aware or are limited in the number of groups they can support due to

issues such as addressing, congestion control and administration (Morse et al. 2000; Morse and Zyda 2001; Fisher 2002; Li and Zhang 2002; Auerbach, Gopal, Kaplan and Kutten 2003; Hosseini and Georganas 2004). These prompted the development of overlay multicast and reliable multicast protocols.

Overlay multicast was developed to provide IP multicast capability over networks that don't offer multicast capability at the network layer and it is usually implemented at the application layer. The most widespread overlay network is the Multicast Backbone or Mbone (Eriksson 1994). The DIVEbone extends the Mbone and is an application-level network architecture built as a stand-alone part of the DIVE toolkit (Frécon et al. 1998). A good overview of Application Layer Multicast (ALM) is given in (Hosseini et al. 2004).

Most authors acknowledge the fact that different multicast applications have different reliability requirements (Floyd, Jacobson, Liu, McCanne and Zhang 1997; Pullen 1999; Singhal et al. 1999; Li et al. 2002; Auerbach et al. 2003). As a result, several reliable multicast approaches have been proposed. Reliable multicasting protocols refer to error-free eventual delivery of information to all the applications with some level of ordering (Li et al. 2002). Floyd et al. (1995; Floyd et al. 1997) describe a Scalable Reliable Multicast protocol for a whiteboard application where each member of the multicast group is responsible for its own correct reception of all the data using a time-out mechanism. Kaser et al. (2000) also examined the scalability of reliable multicast transport but using active services. Pullen (1999) looked at the issue of reliable multicast in DIAs and detailed the workings of the Selectively Reliable Transport Protocol. This protocol employs three service modes according to the requirements of the DIA – best-effort multicast, reliable multicast and reliable datagram. Sato et al. (1999) also proposed a reliable multicast protocol suitable for DIAs that uses the concept of Mutual Aid Regions (MAR). Each MAR has a node that is responsible for acknowledging receipt of packets in that MAR and that sends timeout requests to the nearest MAR if a packet is not received. A good overview of multicast protocols is given in (Lao, Cui, Gerla and Maggiorini 2005) and (Vogel 2004).

Many other application layer protocols exist that exploit the transport and network layer services to optimize delivery of application-specific data. The Real Time Protocol (RTP) provides end-to-end network transport functions suitable for applications transmitting real-time data, such as audio streaming, video streaming or simulation data, over multicast or unicast network services (Schulzrinne and Casner 1993; Perkins and Crowcroft 2000; Schulzrinne, Casner, Frederick and Jacobson 2003). RTP does not address resource reservation and does not guarantee quality-of-service for real-time services. An associated control protocol, RTCP, allows data delivery to be monitored and controlled. Mauve et al. (2001) adapted the RTP for interactive applications by inventing two new complementary protocols: the unreliable Real Time Protocol for Interactive Media (RTP/I) and the Real Time Control Protocol for Interactive Media (RTCP/I). The RTP/I has four distinct data packet types that allow the communication of (1) events, (2) component states, (3) state changes and (4) state queries.

Work performed by Zhang et al. (2002) led to a signalling protocol designed to run over IP called Resource Reservation Protocol (RSVP). This protocol supports both unicast and multicast applications, allowing multiple senders to transmit to multiple groups of receivers and is the main protocol for integrated services or streaming multimedia (Tanenbaum 1996). Kessler and Hodges (1996) proposed a protocol based on queue abstraction to communicate dynamic state information. They categorized communication between tasks of a virtual environment into three types and created an updateable queue for communication messages. Messages are prioritised and may skip or overwrite the queue if they contain a special key. Another protocol, the Interactive Sharing Transfer Protocol, was described by Waters et al. (1997b). This is a hybrid protocol supporting many modes of transport for DIA data. It supports the sharing of information about objects in the DIA, streams audio data via RTP and supports both unicast and multicast communication of state information between ISTP processes.

On the Internet and World Wide Web, 3-dimensional virtual worlds can be constructed using the Virtual Reality Modeling Language (VRML). However, the underlying network support provided by the hypertext transfer protocol (http) is insufficient for large-scale DIAs. Brutzman et al. (1997)

therefore proposed the Virtual Reality Transfer Protocol (VRTP) to facilitate peer-to-peer communications and network monitoring. Another application-independent network protocol, the Distributed Worlds Transfer and communication Protocol (DWTP), was proposed by Broll (1998).

Some standard protocols have been defined for DIAs. The DIS protocol (IEEE 1993; IEEE 1995) strictly defines the information that can be carried by the protocol and limits its possible applications. The High Level Architecture (HLA) protocol tags data at simulation design stage, not at run time, so that it combines dynamic definition of tags and flexibility in the definition of data content (IEEE 2000). More recently, the introduction of XML (extensible Markup Language) by the W3C, has led to the development of the Simple Object Access Protocol (SOAP) for communication between application programs (Jepsen 2001). SOAP allows Remote Procedure Calls (RPCs) between applications independently of the programming language and the operating system.

DIAs employ several different protocols. Modern DIAs employ a mixture of reliable and unreliable transport mechanisms, depending on how critical the data being transmitted is to consistency of the DIA. At the application layer protocols are application specific, although some efforts have been made to standardize these protocols. Protocols may also be downloaded and installed in real-time by the application to ensure optimal communication between remote objects (Watsen and Zyda 1998).

Quality of Service

The previous sections have described how the physical architecture of the underlying network together with appropriate protocols impact both latency and consistency. In this section the concept of Quality of Service (QoS) will be examined. QoS employs protocols to control the network technology so that a certain level of service is guaranteed for a communications flow. A *flow* is a stream of data packets traveling between source and destination network layers (Tanenbaum 1996) and it can be characterised by four primary parameters:

1. Network latency;
2. Latency variance or jitter;
3. Network bandwidth;
4. Transmission reliability.

These determine the QoS of the flow. Several techniques have been developed for achieving good QoS – over provisioning, buffering, traffic shaping, bucket algorithms, resource reservation, admission control, proportional routing and packet scheduling. For streaming multimedia the IETF (Internet Engineering Task Force) has developed Integrated Services Architecture (or flow-based QoS), employing the RSVP mentioned previously (Zhang et al. 2002). This protocol is used to communicate the requirements of the application to the network in a robust and efficient way. Another, simpler architecture is the Differentiated Services Architecture (or class-based QoS). Various schemes exist for managing the service classes such as expedited forwarding and assured forwarding. Another development is Multi-Protocol Label Switching (MPLS), a technique that constructs connection-oriented routes on the fly (Tanenbaum 1996).

There is very little documented research relating DIAs and QoS. QoS may be seen as a set of constraints on the performance of the DIA such as those described by Houatra (2000): fault-tolerance, persistence, interactivity and scalability. Houatra also describes software frameworks for the control and management of QoS in DIAs, by describing the Continuum project. Other attempts have also been made to define QoS architectures for certain aspects of the DIAs. For example Greenhalgh et al. (1999) proposed a QoS architecture for managing streamed video within shared virtual worlds. In their proposal, QoS is driven by dynamically negotiating levels of mutual awareness among entities and by balancing group and individual needs. They emphasize the dynamic nature of user demands in DIAs and the consequent demands for dynamic QoS. How to configure the QoS is also an issue they raise – should a user be able to directly configure and reconfigure QoS for each entity in the DIA? Choukair et

al. (2000b) describe the implementation of QoS control in a DIA platform called VirtualArch which is built on the DVE Collaboration Model (DVECOM). The objectives of integrating QoS are to guarantee consistency and synchronization across the DIA. Choukair and Retailleau (2000a) investigated the integration of QoS with Real-time Constraints (RT-QoS) into DVECOM.

Provision of QoS over the Internet is in a state of flux. For DIAs, issues such as QoS setup times and reconfiguration times may increase network latency, reduce responsiveness and hence make consistency more difficult to maintain. Other issues such as the need for QoS to be scalable and to adapt to real-time requirements, as well as being able to deal with the unpredictable nature of the data generated must not be ignored.

Software Architecture

A DIA is ultimately a software program, albeit usually an extremely complex one. The design and deployment of the software is driven by the requirements of the DIA and the architecture of the underlying network (Singhal et al. 1999). The quality of the software is therefore of fundamental importance and some of the key architectural issues that any successful DIA needs to consider are:

1. **Interactability:** How well can a user interact with the virtual world? This incorporates sensory input/output and real-time graphics rendering. Most consistency control mechanisms aim to meet this requirement.

2. **Interoperability:** How well can different DIAs and associated technologies share information?

There are two aspects of interoperability:

- a. The ability of distinct DIAs and technologies to communicate. The HLA addresses this issue (IEEE 2000);
- b. The ability of the same DIA running on heterogeneous operating systems to communicate.

For example, the use of XML and SOAP in ATLAS II and NPSNET V (Capps,

McGregor, Brutzman and Zyda 2000; Kapolka, McGregor and Capps 2002).

3. **Dynamic Extensibility:** How easily can the software system be updated and modified while executing? In the ATLAS-II application developed at CDS&N labs the objective is to allow the system extend itself automatically, rather than with explicit human intervention. In ATLAS this technique is referred to as *self-tunability* (Lee, Lim and Han 2002). When system degradation is detected or a system reconfiguration message written in XML is received, a component known as the *Resource Discovery Manager* actively locates the new component to be loaded from either a local or remote source. The component is initiated and then registered with the appropriate ATLAS manager. In NPSNET V (Capps et al. 2000), all components are loaded dynamically at run time. In contrast systems such as DIVE (Frécon 2003) or MASSIVE (Greenhalgh, Purbick and Snowdon 2000), load all components each time they execute.

4. **Scalability:** How well can the DIA handle an increasing number of users? For example, although the DIVE architecture is very capable in certain areas such as concurrency, its use is limited by the fact that it is difficult to scale beyond about 32 participants (Carlsson et al. 1993). Massively Multiplayer Online Games have the ability to scale to thousands of simultaneous participants (Anarchy Online 2004). Information management techniques such as dead reckoning and relevance filtering assist in making a DIA more scalable in addition to improving consistency. The design and deployment of the software is driven by the requirements of the DIA and the architecture of the underlying network (Singhal et al. 1999). Most DIA architectures incorporate multithreading to improve the efficiency of the application and manage resources (Singhal et al. 1999; Faisstnauer et al. 2000). Dynamic load balancing, which distributes the work load efficiently among available resources, is used in NetEffect (Das et al. 1997).

Snowdon et al. (Snowdon, Greenhalgh, Benford, Bullock and Brown 1996) reviewed distributed software architectures for networked virtual reality, proposed a reference architecture for distributed virtual reality and identified a number of key components which offer distinct services:

1. Security – authentication and authorisation services;
2. Object support – memory management of persistent and executing object data;
3. Core virtual reality – services such as collision detection and interest management;
4. User interface – handles input and output from multiple devices.

These services are supported by additional services such as event management, database support, 3D graphics rendering and multicast network protocols.

The division of the software into components facilitates the development of new DIAs. For example the Continuum platform developed by Tran et al. (2002) is written entirely in JAVA and is structured in layers, with orthogonal tasks such as object management and network support comprising the layers. These layers can be extended and adapted and they can be fitted together to derive profiles, to construct different types of systems (e.g. a collaborative system and real-time online games). The Continuum Platform is considered middleware as it provides services to the application.

Software deployment is also important. For example in SPLINE (Waters et al. 1997a), the software is spread across four different servers to improve scalability:

1. A session server to handle new connections;
2. A server to handle users with slow connections and interact with them using the client/server model;

3. A locale update server which is responsible for presenting participants with a seamless virtual environment from the various *locales* that it is divided into (Barrus et al. 1996a; Barrus et al. 1996b);
4. A name server for the easy location of entities within the world.

A key component of SPLINE's architecture is the locale update server. Kauster (2000) examined the issue of users congregating in a single locale and thus overloading a single locale update server. The solution proposed by Kauster is referred to as the Asheron's Call architecture. This operates by dynamically distributing the load among other available servers, resulting in a more scalable, more efficient and more reliable system.

At the heart of a DIA is a database. This database is rendered to users in the form of a virtual world and changes to the database must be rendered to interested users in real-time. The existence of latency and the short time limit imposed on rendering imposes constraints on where the database and rendering software are located. Communication across a network is usually impractical and so, the DIA database is usually replicated at each node or on a dedicated server for a LAN.

Software may also be deployed within the network itself. Kasera et al. (2000) proposed using active services to efficiently deliver reliable multicast and hence increase the scalability of the DIA. By placing active services at strategic locations inside the network to control loss recovery and congestion, they demonstrated improved resource usage, speedier loss recovery and congestion control that respects TCP.

This section has given a brief overview of some of the issues that the software architecture must address and that fundamentally impact the performance of the DIA and the user's experience in the simulated world.

III. CONCLUDING REMARKS

This paper (parts I and II) presented a comprehensive survey of the current state of research in techniques for reducing and masking network latency and maintaining consistency in Distributed Interactive Applications. It clarified some fundamental terminology and explored the concept of a DIA. It examined the issues of consistency and latency, and offered a definition for each in the context of DIAs. The connection between latency and consistency was explored. Finally, the paper reviewed the documented methods, mechanisms and architectures available to the DIA designer in maintaining dynamic state consistency and reducing the impact of network latency.

An emerging approach to dealing with consistency and latency in DIAs exploits human perceptual abilities, user awareness and patterns of events, in addition to how users interact with the technology to reduce the quantity of network traffic that needs to be communicated between users (Ryan and Sharkey 1998; Stanney, Mourant and Kennedy 1998; Park and Kenyon 1999; Ruhleder and Jordan 1999; Vaghi, Greenhalgh and Benford 1999; Gutwin 2001; Ruhleder and Jordan 2001; Delaney, Meenaghan, McLoone and Ward 2004; Gutwin, Benford, Dyck, Fraser, Vaghi et al. 2004; Mania, Adelstein, Ellis and Hill 2004; Wolff, Roberts and Otto 2004).

There are several other issues associated with DIAs that are not discussed in this paper. These include how new users should join the DIA (Roberts et al. 1995; Vogel, Mauve, Hilt and Effelsberg. 2003), the exploitation of multimedia networking technologies (Gutwin et al. 2004) and the use of peer-to-peer networks such as Gnutella (Boukerche, Araujo and Laffranchi 2004). In addition there are recent efforts by the Moving Pictures Expert Group (MPEG) to extend MPEG to allow multi-user support (Joslin, Di Giacomo and magnenat-Thalmann 2004). This extension to MPEG-4 is referred to as Multi-user Technology (MUTech). It remains to be seen how quickly these new standards and technologies will be incorporated into DIAs.

ACKNOWLEDGEMENT

This material is based upon works supported by Enterprise Ireland under grants no. SC/2002/129/ and Ircset/SC/04/CS0289.

REFERENCES

- Abrams, H., Watsen, K. & Zyda, M. (1998). Three-Tiered Interest Management for Large-Scale Virtual Environments. *Proceedings of Virtual Reality Systems and Technology (VRST '98)* (pp. 125-129). Taipei, Taiwan: ACM.
- Airey, J. M., Rohlf, J. H. & Frederick P. Brooks, J. (1990). Towards image realism with interactive update rates in complex virtual building environments. *ACM SIGGRAPH Computer Graphics* 24(2): 41-50.
- Anarchy Online (2004) Anarchy Online: <http://www.anarchyonline.com>, (Last accessed January 16 2006).
- Anthes, C., Heinzlreiter, P. & Volkert, J. (2004). An adaptive Network Architecture for Close-coupled Collaboration in Distributed Virtual Environments. *Proceedings of Virtual-Reality Continuum & Its Applications in Industry (VRCAI '04)* (pp. 382-385). Singapore.
- Auerbach, J., Gopal, M., Kaplan, M. & Kutten, S. (2003). Multicast Group Membership Management. *IEEE/ACM Transactions on Networking* 11(1): 166-175.
- Bahadir, K. O. & Halit, O. (1999). Analysis of Dead Reckoning Procedures by using Hybrid Automata. *Proceedings of 3rd IEEE International Workshop on Distributed Interactive Simulation and Real-Time Applications* (pp. 22-29). College Park, Maryland.
- Balikhina, T., Ball, F. & Duce, D. (2002). Distributed Virtual Environments - An Active future? *Proceedings of 20th Eurographics UK Conference* (pp. 33-38). De Montfort University, Leicester: IEEE.

- Barrus, J. W., Waters, R. C. & Anderson, D. B. (1996a). Locales and Beacons: Efficient and Precise Support for Large Multi-user Virtual Environments. *Proceedings of Virtual Reality Annual International Symposium (VRAIS '96)* (pp. 204-212). Santa Clara, California: IEEE.
- Barrus, J. W., Waters, R. C. & Anderson, D. B. (1996b). Locales: Supporting Large Multiuser Virtual Environments. *IEEE Computer Graphics and Applications* 16(6): 50-57.
- Bassiouni, M. (1985). Data compression in scientific and statistical databases. *Software Engineering* 11(10): 1047-1058.
- Bassiouni, M., Williams, H. & Loper, M. (1991). Intelligent filtering algorithms for real-time networked simulators. *Proceedings of IEEE Conference on Systems, Man and Cybernetics* (pp. 309-314). IEEE.
- Bassiouni, M. A., Chiu, M. H., Loper, M., Garnsey, M. & Williams, J. (1997). Performance and reliability analysis of relevance filtering for scalable distributed interactive simulation. *ACM Transactions on Modeling and Computer Simulation* 7(3): 293-331.
- Bassiouni, M. A., Chiu, M.-H., Loper, M., Garnsey, M. & Williams, J. (1998). Relevance filtering for distributed interactive simulation. *Computer Systems Science and Engineering* 13(1): 39-47.
- Bassiouni, M. A. & Mukherjee, A. (1990). Data Compression in real-time distributed Systems. *Proceedings of Global Telecommunications Conference (GLOBECOM)* (pp. 967-971). San Diego, CA: IEEE.
- Baughman, N. E. & Levine, B. N. (2001). Cheat-proof Payout for Centralized and Distributed Online Games. *Proceedings of 20th Annual Joint Conference of the IEEE Computer and Communications Societies (INFOCOM 2001)* (pp. 104-113). Anchorage, Alaska: IEEE.
- Benford, S. & Fahlén, L. E. (1993). A Spatial Model of Interaction for Large Virtual Environments. *Proceedings of Third European Conference on Computer Supported Cooperative Work (ECSCW '93)* (pp. 107-123). Milano, Italy: Kluwer Academic Publishers, Dordrecht.

- Benford, S., Greenhalgh, C. & Lloyd, D. (1997a). Crowded Collaborative Virtual Environments. *Proceedings of SIGCHI conference on Human factors in computing systems* (pp. 59-66). Atlanta, Georgia, United States: ACM Press.
- Benford, S., Reynard, G., Greenhalgh, C., Snowdon, D. & Bullock, A. (2000). Staging a Poetry Performance in a Collaborative Virtual Environment. *IEEE Computer Graphics and Applications* 20(3): 66-75.
- Benford, S. D. & Fahlén, L. E. (1992). Aura, Focus and Awareness. *Proceedings of 5th MultiG Workshop* Royal Institute of Technology, Stockholm, Sweden: Kungl Tekniska Hogskolan.
- Benford, S. D. & Greenhalgh, C. M. (1997b). Introducing Third Party Objects into the Spatial Model of Interaction. *Proceedings of Fifth European Conference on Computer Supported Cooperative Work (ECSCW '97)* (pp. 189-204).
- Blau, B., Hughes, C. E., Moshell, J. M. & Lisle, C. (1992). Networked Virtual Environments. *Proceedings of Symposium on Interactive 3D Graphics* (pp. 157-160). Cambridge, Massachusetts, United States: ACM.
- Boukerche, A., Araujo, R. B. & Laffranchi, M. (2004). A Hybrid Solution to Support Multiuser 3D Virtual Simulation Environments in Peer-to-peer Networks. *Proceedings of Distributed Simulation and Real-Time Applications (DS-RT '04)* (pp. 61-68). Budapest, Hungary: IEEE.
- Broll, W. (1998). DWTP—an Internet protocol for shared virtual environments. *Proceedings of 3rd Symposium on Virtual Reality Modeling Language* (pp. 49-56). Monterey, California, United States.
- Brutzman, D. P., Zyda, M., Watsen, K. & Macedonia, M. R. (1997). Virtual Reality Transfer Protocol (VRTP) Design Rationale. *Proceedings of 6th Workshop on Enabling Technologies on Infrastructure for Collaborative Enterprises (WET-ICE '97)* (pp. 179-186). MIT, Cambridge, MA: IEEE Computer Society.

- Cai, W., Lee, F. B. S. & Chen, L. (1999). An Auto-adaptive Dead Reckoning Algorithm for Distributed Interactive Simulation. *Proceedings of 13th Workshop on Parallel and Distributed Simulation (PADS '99)* (pp. 82-89). Atlanta, Georgia.
- Capin, T. K., Emerald, J. & Thalmann, D. (1999). A dead reckoning technique for streaming virtual human animation. *IEEE Transactions on Circuits and Systems for Video Technology* 9(3): 411-414.
- Capin, T. K., Pandzic, I., Thalmann, S., Magnenat, N. & Thalmann, D. (1997). A Dead-reckoning Algorithm for Virtual Human Figures. *Proceedings of Virtual Reality Annual International Symposium (VRAIS '97)* (pp. 161-169). Albuquerque, New Mexico: IEEE.
- Capps, M., McGregor, D., Brutzman, D. P. & Zyda, M. (2000). NPSNET-V. A new beginning for dynamically extensible virtual environments. *IEEE Computer Graphics and Applications* 20(5): 12-15.
- Capps, M. & Teller, S. (1997). Communication visibility in shared virtual worlds. *Proceedings of 6th Workshop on Enabling Technologies on Infrastructure for Collaborative Enterprises (WET-ICE '97)* (pp. 187-192). Cambridge, MA: IEEE.
- Carlsson, C. & Hagsand, O. (1993). DIVE - A Platform for Multi-User Virtual Environments. *Computers and Graphics* 17(6): 663-669.
- Caro, A., L. Jr, Iyengar, J. R., Amer, P. D., Ladha, S., Heinz, G. J. I. & Shah, K. C. (2003). SCTP: A proposed Standard for Robust Internet Data Transport. *IEEE Computer* 36(11): 56-63.
- Cheshire, S. (1996) Latency and the quest for interactivity: <http://www.stuartcheshire.org/>, (Last accessed January 16 2006).
- Choukair, Z. & Retailleau, D. (2000a). Integrating QoS to Collaborative Distributed Virtual Reality Applications. *Proceedings of 3rd International Symposium on Object-Oriented Real-time Distributed Computing* (pp. 320-327). Newport Beach, CA, USA: IEEE.

- Choukair, Z., Retailleau, D. & Hellstrom, M. (2000b). Environment for performing collaborative distributed virtual environments with QoS. *Proceedings of 7th International Conference on Parallel and Distributed Systems (ICPADS'00)* (pp. 111-118). Iwate, Japan.
- Das, T. K., Singh, G., Mitchell, A., Kumar, P. S. & McGee, K. (1997). NetEffect: a network architecture for large-scale multi-user virtual worlds. *Proceedings of ACM Symposium on Virtual Reality Software and Technology* (pp. 157-163). Lausanne, Switzerland: ACM.
- de Oliveira, J. & Georganas, N. D. (2003). VELVET: An Adaptive Hybrid Architecture for VErY Large Virtual EnvironmenTs. *Presence: Teleoperators and Virtual Environments* 12(6): 555-580.
- Deering, E. S. (1989). RFC-1112 - Hosting Extensions for IP Multicasting. *Proceedings of*
- Deering, E. S. & Cheriton, D. R. (1990). Multicast Routing in Datagram Internetworks and Extended LANs. *ACM Transactions on Computer Systems* 8(2): 85-110.
- Delaney, D., Meeneghan, P., McLoone, S. & Ward, T. (2004). Examining User Performance in the presence of Latency and Jitter in Distributed Interactive Applications. *Proceedings of Irish Signals and Systems Conference (ISSC)* (pp. 323-328). Belfast: IEE.
- Delaney, D., Ward, T. & Mc Loone, S. (2003a). On Reducing Entity State Update Packets in Distributed Interactive Simulations using a Hybrid Model. *Proceedings of 21st IASTED International Multi-conference on Applied Informatics* (pp. 833-838). Innsbruck, Austria.
- Delaney, D., Ward, T. & Mc Loone, S. (2003b). Reducing Update Packets in Distributed Interactive Applications using a Hybrid Model. *Proceedings of 16th International Conference on Parallel and Distributed Computing Systems* (pp. 417-422). Reno, USA.
- Delaney, D., Ward, T. & McLoone, S. (2006). On Consistency and Network Latency in Distributed Interactive Applications: A Survey - Part I. *Presence: Teleoperators and Virtual Environments* 15(2): XXX-XXX.

- Dourish, P. (1995). The Parting of Ways: Divergence, Data Management and Collaborative Work. *Proceedings of 4th European Conference on Computer Supported Cooperative Work (ECSCW '95)* (pp. 215-230). Stockholm: Kluwer Academic Publishers, Dordrecht.
- Duncan, T. P. & Gracanin, D. (2003). Pre-Reckoning algorithm for Distributed Virtual Environments. *Proceedings of Winter Simulation Conference* (pp. 1086-1093).
- Durbach, C. & Fourneau, J. M. (1998). Performance Evaluation of a Dead Reckoning Mechanism. *Proceedings of 2nd International Workshop on Distributed Simulation and Real Time Applications (DS-RT '98)* (pp. 23-29). Atlanta, Georgia: IEEE.
- Eriksson, H. (1994). MBone: The Multicast BackBone. *Communications of the ACM* 37(8): 54-60.
- Faisstnauer, C., Schmalstieg, D. & Purgathofer, W. (2000). Priority Round-Robin Scheduling for very large Virtual Environments. *Proceedings of Virtual Reality (VR '00)* (pp. 135-142). New Brunswick, NJ, USA: IEEE Computer Society.
- Fisher, H. (2002). Multicast Issues for Collaborative Virtual Environments. *IEEE Computer Graphics and Applications* 22(5): 68-75.
- Floyd, S., Jacobson, V., Liu, C., McCanne, S. & Zhang, L. (1997). A Reliable Multicast Framework for Light-weight Sessions and Application Level Framing. *IEEE/ACM Transactions on Networking* 5(6): 784-803.
- Floyd, S., Jacobson, V., McCanne, S., Liu, C.-G. & Zhang, L. (1995). Reliable Multicast Framework for Light-Weight Sessions and Application Level Framing. *Proceedings of Applications, Technologies, Architectures and Protocols for Computer Communication* (pp. 342-356). Cambridge, Massachusetts, United States: ACM SIGCOMM.
- Frécon, E. (2003). DIVE: A generic tool for the development of virtual environments. *Proceedings of 7th International Conference on Telecommunications (ConTEL 2003)* (pp. 345-352). Zagreb, Croatia.

- Frécon, E. & Stenius, M. (1998). DIVE: A Scalable Network Architecture for Distributed Virtual Environments. *Distributed Systems Engineering Journal* 5: 91-100.
- Funkhouser, T. A. (1995). RING: A client-server system for multiuser virtual environments. *Proceedings of Symposium on Interactive 3D Graphics* (pp. 85-92). Monterey, California, United States: ACM SIGGRAPH.
- Greenhalgh, C. (1999). Large Scale Collaborative Virtual Environments. London, UK, Springer-Verlag.
- Greenhalgh, C. & Benford, S. (1995). MASSIVE: a collaborative virtual environment for teleconferencing. *ACM Transactions on Computer-Human Interaction (TOCHI)* 2(3): 239-261.
- Greenhalgh, C. & Benford, S. (1997). Boundaries, Awareness and Interaction in collaborative Virtual Environments. *Proceedings of 6th Workshop on Enabling Technologies on Infrastructure for Collaborative Enterprises (WET-ICE '97)* (pp. 193-198). Cambridge, MA: IEEE.
- Greenhalgh, C., Benford, S. & Reynard, G. (1999). A QoS Architecture for Collaborative Virtual Environments. *Proceedings of 7th International Conference on Multimedia* (pp. 121-130). Orlando Florida, USA: ACM Press.
- Greenhalgh, C., Purbick, J. & Snowdon, D. (2000). Inside MASSIVE-3: Flexible Support for Data Consistency and World Structuring. *Proceedings of 3rd International Conference on Collaborative Virtual Environments* (pp. 119-127). San Francisco, California: ACM Press.
- Gutwin, C. (2001). The Effects of Network Delays on Group Work in Real-Time Groupware. *Proceedings of 7th European Conference on Computer-supported Cooperative Work (ECSCW '01)* (pp. 299-318). Boon, Germany: Kluwer Academic Publishers, Dordrecht.
- Gutwin, C., Benford, S., Dyck, J., Fraser, M., Vaghi, I. & Greenhalgh, C. (2004). Revealing Delay in Collaborative Environments. *Proceedings of International conference on Human-Computer Interaction* (pp. 503-510). Vienna, Austria: ACM.

- Han, S., Lim, M. & Lee, D. (2000). Scalable interest management using interest group based filtering for large networked virtual environments. *Proceedings of Symposium on Virtual Reality Software and Technology (VRST '00)* (pp. 103-108). Seoul, South Korea: ACM.
- Hook, D. J. V., D., J. C., Newton, M. & Fusco, D. (1994). An Approach to DIS Scalability. *Proceedings of 11th Workshop in Standards for the Interoperability of Distributed Simulation* (pp. 347-355).
- Hosseini, M. & Georganas, N. D. (2004). End System Multicast Protocol for Collaborative Virtual Environments. *Presence: Teleoperators and Virtual Environments* 13(3): 263-278.
- Houatra, D. (2000). QoS-constrained Event Communications in Distributed Virtual Environments. *Proceedings of 2nd International Symposium on Distributed Objects and Applications* (pp. 71-80). IEEE.
- IEEE (1993). IEEE Standard for Distributed Interactive Simulation - Application Protocols. *Proceedings of IEEE Std 1278-1993* New York: IEEE.
- IEEE (1995). IEEE Standard for Distributed Interactive Simulation - Application Protocols. *Proceedings of IEEE Std 1278.1-1995 (Revision of IEEE Std 1278-1993)*: IEEE.
- IEEE (2000). Modelling and Simulation (M&S) High Level Architecture (HLA) - Framework and Rules. *Proceedings of IEEE Std 1516-2000*.
- Jepsen, T. (2001). SOAP Cleans up Interoperability Problems on the Web. *IT Professional* 3(1): 52-55.
- Joslin, C., Di Giacomo, T. & magnenat-Thalmann, N. (2004). Collaborative Virtual Environments: From birth to Standardization. *IEEE Communications Magazine*. **44**: 28-33.
- Kapolka, A., McGregor, D. & Capps, M. (2002). A unified component framework for dynamically extensible virtual environments. *Proceedings of 4th International Conference on Collaborative Virtual Environments (CVE02)* (pp. 64-71). Bonn, Germany.
- Kasera, S. K., Bhattacharyya, S., Keaton, M., Kiwior, D., Zabele, S., Kurose, J. & Towsley, D. (2000). Scalable Fair Reliable Multicast Using Active Services. *IEEE Network*: 48-57.

- Kessler, G. D. & Hodges, L. D. (1996). A Network Communication Protocol for Distributed Virtual Environment Systems. *Proceedings of Virtual Reality Annual International Symposium (VRAIS '96)* (pp. 214-221). Santa Clara, California: IEEE Computer Society.
- Koster, R. (2000) Insubstantial Pageants: Designing Virtual Worlds: <http://www.legendmud.org/raph/gaming/book.html>, (Last accessed January 16 2006).
- Krumm-Heller, A. & Taylor, S. (2000). Using determinism to improve the accuracy of dead reckoning algorithms. *Proceedings of SimTecT2000 - The Simulation Technology and Training Conference* Sydney, Australia: Simulation Industry Association of Australia.
- Kwang-Hyun, S. & Jong-Sung, K. (2001). A Dead reckoning Algorithm with variable threshold scheme in networked virtual environment. *IEEE Conference on Systems, Man and Cybernetics 2*: 1113-1118.
- Lao, L., Cui, J.-H., Gerla, M. & Maggiorini, D. (2005). A Comparative Study of Multicast Protocols: Top, Bottom, or In the Middle? *Proceedings of Los Angeles, CA: Computer Science Department, University of California, Los Angeles, CA 90095*.
- Lea, R., Honda, Y., Matsuda, K. & Matsuda, S. (1997). Community Place: architecture and performance. *Proceedings of Second Symposium on Virtual Reality Modeling Language* (pp. 41-50). Monterey, California, United States: ACM Press.
- Lee, B. S., Cai, W., Turner, S. J. & Chen, L. (2000). Adaptive Dead Reckoning algorithms for distributed Interactive Simulation. *International Journal of Simulation: Systems, Science & Technology 1*(1-2): 21-34.
- Lee, D., Lim, M. & Han, S. (2002). ATLAS - A Scalable Network Framework for Distributed Virtual Environments. *Proceedings of 4th International Conference on Collaborative Virtual Environments (CVE02)* (pp. 47-54). Bonn, Germany.
- Lee, D., Yang, J., Yoon, H. Y., Yu, C. & Hyun, S. J. (2000). Entity-Centric Scalable Concurrency Control for Distributed Interactive Applications. *Proceedings of International Performance,*

- Computing, and Communications Conference (IPCCC '00)* (pp. 544-550). Phoenix, Arizona, USA: IEEE.
- Li, V. O. K. & Zhang, Z. (2002). Internet Multicast Routing and Transport Control Protocols. *Proceedings of the IEEE 90*(3): 360-391.
- Liang, L. A. H., CAI, W., Lee, B. S. & Turner, S. J. (1999). Performance Analysis of Packet Bundling Techniques in DIS. *Proceedings of 3rd International Workshop on Distributed Simulation and Real Time Applications (DS-RT '99)* (pp. 75-82). College Park, Maryland: IEEE.
- Lin, K.-C., Blair, J. L. & Woodyard, J. M. (1997). Study on Dead-Reckoning Translation in High-Level Architecture. *Simulation 69*(2): 103-109.
- Lin, K.-C. & Schab, D. E. (1994). The performance assessment of the dead reckoning algorithms in DIS. *Simulation 63*(5): 318-325.
- Lui, J. C. S. (2001). Constructing Communication Subgraphs and Deriving an Optimal Synchronization Interval for Distributed Virtual Environment Systems. *IEEE Transactions on Knowledge and Data Engineering 13*(5): 778-792.
- Macedonia, M. R., Zyda, M. J., Pratt, D. R., Barham, P. T. & Zeswitz, S. (1994). NPSNET: A Network Software Architecture for Large Scale Virtual Environments. *Presence: Teleoperators and Virtual Environments 3*(4): 265-287.
- Macedonia, M. R., Zyda, M. J., Pratt, D. R., Brutzman, D. P. & Barham, P. T. (1995). Exploiting Reality with Multicast Groups. *IEEE Computer Graphics and Applications 15*(5): 38-45.
- Makbily, Y., Gotsman, C. & Bar-Yehuda, R. (1999). Geometric Algorithms for Message Filtering in Decentralized Virtual Environments. *Proceedings of Symposium on Interactive 3D Graphics* (pp. 39-46). Atlanta, Georgia, USA: ACM.
- Mania, K., Adelstein, B. D., Ellis, S. R. & Hill, M. I. (2004). Perceptual sensitivity to head tracking latency in virtual environments with varying degrees of scene complexity. *Proceedings of 1st*

Symposium on Applied perception in graphics and visualization (pp. 39-47). Los Angeles, California.

- Mauve, M., Hilt, V., Kuhmunch, C. & Effelsberg, W. (2001). RTP/I - Towards a Common Application Level Protocol for Distributed Interactive Media. *IEEE Transactions on Multimedia* 3(1): 152-161.
- McGregor, D., Kapolka, A., Zyda, M. & Brutzman, D. P. (2003). Requirements for Large-Scale Virtual Environments. *Proceedings of 7th International Conference on Telecommunications (ConTEL 2003)* (pp. 353-358). Zagreb, Croatia.
- Morse, K. L., Bic, L. & Dillencourt, M. (2000). Interest Management in large-scale virtual environments. *Presence: Teleoperators and Virtual environments* 9(1): 52-68.
- Morse, K. L. & Zyda, M. (2001). Multicast Grouping for Data Distribution Management. *Simulation Practice and Theory* 9(1-2): 121-141.
- Ozutam, B. K. & Oguztuzun, H. (1999). Analysis of Dead Reckoning Procedures by using Hybrid Automata. *Proceedings of 3rd International Workshop on Distributed Simulation and Real Time Applications (DS-RT '99)* (pp. 22-29). College Park, Maryland.
- Pandzic, I. S., Lee, E., Thalmann, N. M., Capin, T. K. & Thalmann, D. (1997). A Flexible Architecture for Virtual Humans in Networked Collaborative Virtual Environments. *Computer Graphics Forum* 16(3): 177-188.
- Park, K. S. & Kenyon, R. V. (1999). Effects of Network Characteristics on Human Performance in a Collaborative Virtual Environment. *Proceedings of Virtual Reality (VR '99)* (pp. 104-111). Houston, Texas: IEEE Computer Society.
- Perkins, C. & Crowcroft, J. (2000). Notes on the use of RTP for shared workspace applications. *ACM Computer Communication Review* 30(2): 35-40.
- Pullen, J. M. (1999). Reliable Multicast network Transport for Distributed Virtual Simulation. *Proceedings of 3rd International Workshop on Distributed Simulation and Real Time Applications (DS-RT '99)* (pp. 59-66). College Park, Maryland: IEEE.

- Rak, S. J. & Van Hook, D. J. (1996). Evaluation of Grid-based Relevance Filtering for Multicast Group Assignment. *Proceedings of 14th Workshop on Standards for the Interoperability of Distributed Simulations* (pp. 739-747). Florida, USA.
- Roberts, D. J. (2004). Communication Infrastructures for Inhabited Information Spaces in Inhabited Information Spaces: Living With Your Data (Computer Supported Cooperative Work). D. N. Snowdon, E. F. Churchill and E. Frecon. London, Springer-Verlag: pp.233-267.
- Roberts, D. J., Sharkey, P. M. & Sandoz, P. D. (1995). A Real-time Predictive Architecture for Distributed Virtual Reality. *Proceedings of 1st Workshop on Simulation and Interaction in Virtual Environments* (pp. 279-288). Iowa City: ACM SIGGRAPH.
- Roberts, D. J., Strassner, J., Worthington, B. G. & Sharkey, P. M. (1999). Influence of the supporting protocol on the latencies induced by concurrency control within large scale multiuser distributed virtual reality system. *Proceedings of International Conference on Virtual Worlds and Simulation (VWSIM), SCS Western Multi-conference '99* (pp. 70-75). San Francisco, California.
- Robinson, M., Pekkola, S., Korhonen, J., Hujala, S., Toivonen, T. & M.-J.Saarinen (2001). Extending the Limits of Collaborative Virtual Environments in Collaborative Virtual Environments: Digital Places and Spaces for Interaction. E. Churchill, D. Snowdon and A. Munro. London Berlin Heidelberg, Germany, Springer-Verlag.
- Roehle, B. (1997). Channeling the data flood. *IEEE Spectrum* 34(3): 32-38.
- Ruhleder, K. & Jordan, B. (1999). Meaning-making across remote sites: How delays in transmission affect interaction. *Proceedings of Sixth European Conference on Computer Supported Cooperative Work (ECSCW '99)* (pp. 411-429). Copenhagen, Denmark: Kluwer Academic Publishers.
- Ruhleder, K. & Jordan, B. (2001). Co-Constructing Non-Mutual Realities: Delay-Generated Trouble in Distributed Interaction. *Computer Supported Cooperative Work (CSCW '01)* 10: 113-138.

- Russo, K. L., Shuette, L. C., Smith, J. E. & McGuire, M. E. (1995). Effectiveness of Various New Bandwidth Reduction Techniques in ModSAF. *Proceedings of 13th Workshop on Standards for the Interoperability of Distributed Simulations* (pp. 587-591). Orlando, FL.
- Ryan, M. D. & Sharkey, P. M. (1998). Distortion in Distributed Virtual Reality. *Proceedings of First International Conference on Virtual Worlds* (pp. 42-48). Paris: Springer-Verlag.
- Sato, F., Minamihata, K., Fukuoka, H. & Mizuno, T. (1999). A reliable multicast framework for Distributed Virtual Reality Environment. *Proceedings of International Workshop on Parallel Processing* (pp. 588-593). Aizu-Wakamatsu, Japan.
- Schulzrinne, A. & Casner, S. L. (1993). RTP: A Transport Protocol for Real-time Applications. *Proceedings of Internet Engineering Task Force - Internet Draft*.
- Schulzrinne, H., Casner, S., Frederick, R. & Jacobson, V. (2003). RFC 3550 - RTP: A Transport Protocol for Real-Time Applications. *Proceedings of*.
- Shaw, C., Green, M., Liang, J. & Sun, Y. (1993). Decoupled simulation in virtual reality with the MR toolkit. *ACM Transactions on Information Systems (TOIS) 11(3)*: 287-317.
- Singh, G., Serra, L., Png, W. & Ng, H. (1994). BrickNet - A Software Toolkit for Network-based Virtual Worlds. *Presence: Teleoperators and Virtual Environments 3(1)*: 19-34.
- Singhal, S. K. (1996) Effective Remote Modelling in Large-scale Distributed Simulation and visualisation environments., Academic, Department
- Singhal, S. K. & Cheriton, D. R. (1995). Exploiting Position History for Efficient Remote Rendering in Networked Virtual Reality. *Presence: Teleoperators and Virtual Environments 4(2)*: 169-194.
- Singhal, S. K. & Zyda, M. (1999). Networked Virtual Environments. New York, ACM Press.
- Snowdon, D., Greenhalgh, C., Benford, S., Bullock, A. & Brown, C. (1996). A Review of Distributed Architectures for Networked Virtual Reality. *Virtual Reality: Research, Development and Applications 2(1)*: 155-175.

- Stanney, K. M., Mourant, R. R. & Kennedy, R. S. (1998). Human Factors Issues in Virtual Environments :A Review of the Literature. *Presence: Teleoperators and Virtual Environments* 7(4): 327–351.
- Steed, A. & Angus, C. (2004). Frontier Sets: A Partitioning Scheme to Enable Scalable Virtual Environments. *Proceedings of EUROGRAPHICS 2004, Short Presentations and Interactive Demos* (pp. 13-17). Grenoble, France.
- Steed, A. & Angus, C. (2005). Supporting Scalable Peer to Peer Virtual Environments using Frontier Sets. *Proceedings of IEEE Virtual Reality* (pp. 27-34). Bonn, Germany: IEEE.
- Tanenbaum, A. S. (1996). Computer Networks, Prentice Hall.
- Tran, F. D., Deslaugiers, M., Gérodolle, A., Hazard, L. & Rivierre, N. (2002). An Open Middleware for Large-scale Networked Virtual Environments. *Proceedings of Virtual Reality (VR '02)* (pp. 22-29). Orlando, FL, USA: IEEE Computer Society.
- Vaghi, I., Greenhalgh, C. & Benford, S. (1999). Coping with inconsistency due to network delays in collaborative virtual environments. *Proceedings of Symposium on Virtual Reality Software and Technology (VSRT '99)* (pp. 42-49). London, England: ACM.
- Vogel, J. (2004) Consistency Algorithms and Protocols for Distributed Interactive Applications, PhD Thesis, Academic, Department University of Mannheim, Germany;
- Vogel, J., Mauve, M., Hilt, V. & Effelsberg., W. (2003). Late Join Algorithms for Distributed Interactive Applications. *Multimedia Systems* 9(4): 327-336.
- Waters, R. C., Anderson, D. B., Barrus, J. W., Brogan, D. C., Casey, M. A., McKeown, S. G., Nitta, T., Sterns, I. B. & Yerazunis, W. S. (1997a). Diamond Park and Spline: A Social Virtual Reality System with 3D Animation, Spoken Interaction, and Runtime Modifiability. *Presence: Teleoperators and Virtual Environments* 6(4): 461-480.

- Waters, R. C., Anderson, D. B. & Schwenke, D. L. (1997b). Design of the Interactive Sharing Transfer Protocol. *Proceedings of 6th Workshop on Enabling Technologies on Infrastructure for Collaborative Enterprises (WET-ICE '97)* (pp. 140-147). IEEE.
- Watsen, K. & Zyda, M. (1998). Bamboo - A Portable System for Dynamically Extensible, Real-time, Networked, Virtual Environments. *Proceedings of Virtual Reality Annual International Symposium (VRAIS '98)* (pp. 252-259). Atlanta, Georgia: IEEE.
- Wolff, R., Roberts, D. J. & Otto, O. (2004). A Study of Event Traffic During the Shared Manipulation of Objects Within a Collaborative Virtual Environment. *Presence: Teleoperators & Virtual Environments 13(3)*: 251-262.
- Zeigler, B. P., Cho, H., Lee, J. S., Cho, Y. K. & Sarjoughian, H. S. (1999). Predictive Contract Methodology and Federation Performance. *Proceedings of Fall Simulation Interoperability Workshop (SIW '99)* Orlando, Florida.
- Zhang, L., Deering, S., Estrin, D., Shenker, S. & Zappala, D. (2002). RSVP: A new Resource Reservation Protocol. *IEEE Communications Magazine 14(5)*: 116-127.
- Zou, L., Ammar, M. H. & Diot, C. (2001). An evaluation of grouping techniques for state dissemination in networked multi-user games. *Proceedings of 9th International Symposium on Modeling, Analysis and Simulation of Computer and Telecommunication Systems* (pp. 33-40).