SomeCast

A Paradigm for Real-Time Adaptive Reliable Multicast*

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Abstract

SomeCast is a novel paradigm for the reliable multicast of real-time data to a large set of receivers. SomeCast is *receiver-initiated* and thus scalable in the number of receivers, the diverse characteristics of paths between senders and receivers, and the dynamic conditions of such paths. SomeCast enables receivers to dynamically adjust the rate at which they receive multicast information to enable the satisfaction of their QoS constraints. This is done by enabling a receiver to join Some number of concurrent multiCast sessions, whereby each session delivers a portion of an encoding of the real-time data. By adjusting the number of such sessions dynamically, client-specific QoS constraints are met independently. The SomeCast paradigm can be thought of as a generalization of the AnyCast and ManyCast paradigms, which have been proposed in the literature to address issues of scalability of UniCast and MultiCast environments, respectively. In this paper we overview the SomeCast paradigm, describe an instance of a SomeCast protocol, and present simulation results that quantify the significant advantages gained from adopting such a protocol.

1. Introduction

The ubiquity of the Internet in our society has encouraged the development of many applications that are inherently of a real-time nature—or that deal with information that is inherently temporal in nature. The communication of real-time (RT) information over the Internet is challenging due to the inherent unpredictability involved in using such an open infrastructure. This unpredictability is documented in a number of studies that confirm the highly variable nature of Internet traffic over a multitude of time scales [9, 10, 11], and the futility of techniques such as buffering to eliminate such variability [25].

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Motivation: An important class of RT applications requires the communication of the same content to a very large number of receivers. To cope with the highly-variable nature of network congestion, applications often (a) trade reliability for timeliness, (b) trade timeliness for reliability, or (c) trade resources for both timeliness and reliability.

Trading reliability for timeliness involves the use of a rate-based transport (e.g. using UDP for the communication of audio/video streams as with the MBone multicast protocol). This approach results in the deployment of congestion-insensitive applications, and is viewed by the Internet community as a bad practice [21]. Even if acceptable, such an approach would only be useful for RT Internet applications that are able to tolerate some degree of unreliability (i.e. packet losses). For many RT applications, such unreliability is intolerable. Examples include group simulations, live auctions, RT content replication for Web portals, and stock brokerage applications. Such applications require a multicast infrastructure that is both *real-time* and *reliable* [30].

Trading timeliness (i.e. temporal redudancy) for reliability is evident in all communication protocols that use retransmissions to recover from packet losses due to network congestion (including TCP). An example of this approach for multicast communication is the Scalable Reliable Multicast (SRM) [14], the Cyclic UDP Multicast [2], and the Digital Fountain Multicast [6] paradigms. Obviously, such techniques are not adequate for RT applications, for which "a late packet is a lost packet".

Trading resources (i.e. spatial redundancy) for reliability is common for mission-critical systems that cannot tolerate recovery delays (e.g. using NMR in collision avoidance systems) or for system with irrecoverable failure modes (e.g. using mirror disks to protect against a disk crash). While a widely accepted practice for hard RT systems, the trading of resources for reliability and/or timeliness is not common for systems with "softer" or no deadline constraints—over the Internet, for example.

Paper Overview: In this paper, we argue that the use of redundant resources to improve the reliability and timeliness of Internet applications in general (and multicast communication in particular) is appropriate due to the *already existing* multiplicity of resources in such systems—a multiplicity that is required for performance and scalability purposes. To that end, we present SomeCast—a multicast paradigm that enables the satisfaction of timing constraints *without* sacrificing communication reliability. This is done by enabling receivers to dynamically adjust the rate at which they receive multicast information to guarantee the satisfaction of RT QoS constraints. This rate adjustment is made possible by enabling a receiver to join SOME number of concurrent multiCAST sessions, whereby each session delivers a portion of an encoding of the RT data. By adjusting the number of such sessions dynamically, client-specific QoS constraints can be met independently. SomeCast is a generalization of the AnyCast and ManyCast paradigms, which address issues of scalability of UniCast and MultiCast environments, respectively. SomeCast is *receiver-initiated* and thus scalable in the number of receivers, the diverse characteristics of paths between senders and receivers (e.g. RTT and bandwidth), and the dynamic conditions of such paths (e.g. congestion-induced delays and losses).

2. Related Work

ARQ-based Techniques: Using (Automatic Repeat reQuest), the sender retransmits lost data upon request from the receiver. A straightforward application of ARQ in a multicast setting results in the *NACK implosion* problem, when every receiver sends a NACK message to request retransmission of the same packet. To prevent NACK implosion, the Xpress Transport Protocol (XTP) [31] requires a receiver to multicast control packets to the entire group. A receiver waits for a random time before sending a NACK packet, and refrains from sending a NACK if it sees a NACK from another receiver for the same packet. SRM (Scalable Reliable Multicast) [14] uses similar mechanisms to control the sending of request (NACK) and repair (retransmitted data) packets. As we hinted earlier, retransmission-based approaches trade timeliness for reliability and hence are not useful for the class of multicast applications that require *both* reliability and timeliness.

Deadline-Cognizant Techniques: Most reliable transport protocols (unicast or multicast) are incognizant of the temporal semantics of the data being communicated. Thus, a reliable transport protocol may end up wasting resources attempting to recover from the loss of a packet that is of no value to the receiver (because it is late). Such wasteful resource utilization may result in delaying more packets, resulting in further violations of timeliness constraints. The work of Li, Ha, Varghavan [18] is an example of an approach that attempts to address such a scenario. While this technique was proposed primarily for unicast communication (namely TCP), it is conceivable that similar techniques could be used to avoid unecessary retransmissions in a multicast environment (e.g. SRM). Deadline cognizance is likely to improve the timeliness of a reliable communication by preserving network resources, but it is unable to mask (or hide) the delays resulting from congestion between a sender and a receiver.

FEC-based Techniques: Using FEC, the original data is encoded to obtain additional repair packets that are used to recover from data packet loss. Examples of this approach include the SHARQFEC protocol of Kermode [17], the RT reliable multicast of Rubenstein, Kurose, and Towsley [28] and our recently proposed Adaptive Reliable Multicast (ARM) protocol [32]. FEC-based techniques enable a more efficient/timely recovery from packet losses, but they are not deadline-aware.

Multi-Layer-based Techniques: One approach to providing scalable reliable multicast is the use of multiple channels (or layers), whereby receivers experiencing a higher degree of losses join more channels to recover lost packets. An example of this approach is the work of Kasera, Hjalmtysson, Towsley, and Kurose [16]. While effective in dealing with the variability of loss characteristics across a large set of receivers, this approach does not allow receivers experiencing high loss rates to recover from such losses in a timely fashion. In other words, the reliability of a multicast is guaranteed, but not its timeliness.

AnyCast-based Techniques: *AnyCasting* speeds up access by enabling the selection of "the best" server to fulfill a client's request. Such selection could be done at the server (e.g. the *AnyCast* paradigm of Fei, Bhattacharjee, Zegura, and Ammar [12]) or at the client (e.g. the Dynamic Server Selection protocol of Carter and Crovella [8]). While these techniques were proposed primarily for unicast communication, a similar AnyCast paradigm could be used to select the "best" multicast group for a given receiver (out of many possible alternatives offering the same service) [13]. Given the high variability in network conditions, AnyCast-based techniques are unlikely to be effective for applications that involve a prolonged communication session (e.g. VOD).

ManyCast-based Techniques: *ManyCasting* speeds up access to popular content by enabling clients to access replicated sources concurrently. This is exemplified in the work of Byers, Luby, and Mitzenmacher [7], which uses Tornado encoding to ensure the efficiency of the retrieval and reconstruction processes. While not addressing the problem of RT reliable multicast specifically, this work is similar to ours in that it enables a receiver to communicate concurrently with many senders.

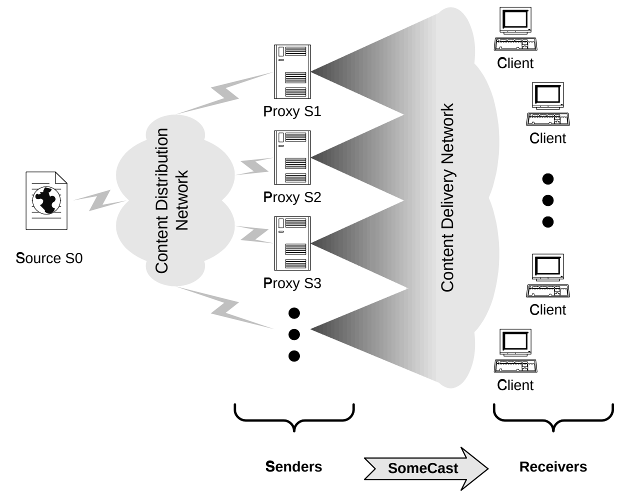


Figure 1. The SomeCast Paradigm

3. Overview of the SomeCast Paradigm

Under the (*client-based*) SomeCast paradigm, clients are empowered to exploit the multiplicity of resources so as to meet specific reliability and RT QoS constraints. It enables multiple resources available in an inherently best-effort environment to be leveraged to achieve a prescribed QoS. A client (or receiver) contacts "some" providers of service as needed. The delegation of QoS management to clients is attractive because it enables the receivers to have very diverse QoS requirements without resulting in a state-explosion problem at the sender (or network).

SomeCast Content Delivery Architecture: Figure 1 illustrates the general architecture of a SomeCast system. We assume that "content" is to be delivered from a *source* to a potentially very large number of *receivers* (or clients) through a number of *senders*, each of which acts as a proxy of the source (i.e. as an outlet for the content).[1] Under SomeCast, each sender sets up a multicast group and a receiver joins as many multicast groups as *necessary* to satisfy its QoS constraints, in an adaptive fashion.

It is important to emphasize that there are *two* "distribution" problems in the architecture depicted in Figure 1: (1) the source must distribute the content to its proxies (the senders), and (2) the senders must relay that content to the receivers. These two problems are quite different. In the first, the system is "closed" in the sense that the set of proxies are all known *a priori*, and are (most likely) within the confines of a single organization or network (e.g. content replication services on the Internet [1, 29]). In the second, the system is "open" in the sense that the (potentially very large) set of receivers are not known *a priori*; they operate independently and may require significantly different QoS. The SomeCast paradigm addresses the challenges posed by the second of the above two distribution problems.[2]

Another important consideration in the architecture depicted in Figure 1, is the nature of the content being distributed. Two possibilities exist: (1) the content comprises a single object (e.g. current bids) that is updated frequently by the source, or (2) the content comprises a live feed (e.g. prices on the stock exchange) that is constantly generated at the source. The SomeCast paradigm can be used to support *both* of these models.

Under the first model, senders act as *repeaters*. They continuously and repeatedly multicast the most-up-to-date content on their respective multicast groups. Receivers join as many such multicast groups as necessary to retrieve such content in a timely fashion. The continuous, periodic retransmission of content by senders is similar to the Broadcast Disk techniques proposed in [3], the Digital Fountain techniques proposed in [6], and the Cyclic Best Effort UDP Protocol proposed in [2]. Thus, under this model, content flows in a store-and-forward fashion from the source to the senders and then from the senders to the receivers. Example applications that fit that model would be the multicast of radar information, or the multicast of the status of an on-

[1] This architecture—comprising a large number of servers acting as proxies for a single content source—is quickly being accepted as inevitable for scalable Internet systems [1, 29, 15].

[2] There are many products in the market-place that address the distribution of content from source to proxies [15, 30].

line auction. Under the second model, senders act as *relays*. They receive a segment of the stream, which they multicast once on their respective multicast groups. Receivers join as many such multicast groups as necessary to be able to recover such segments in a timely fashion (i.e. before the senders switch to the next segment). Thus, under this model, content flows in a pipelined fashion from the source to the senders to the receivers. Example applications that fit that model would be the multicast of live feeds from a stock market exchange, or the multicast of sensory information or live video.

From the perspective of distributing content from the proxies (i.e. senders) to the receivers, the problem is identical under both models. Thus, to simplify our presentation, for the rest of this paper (and without loss of generality), we assume that the first of the above two models is in play.

Reed-Solomon Encoding in SomeCast: In SomeCast, receivers receive the multicast content from multiple senders. Thus, a key component of the SomeCast paradigm is the use of a mechanism that ensures that the various segments of content (received from the various senders) are independent, and thus can be combined efficiently to obtain the original content. To that end, SomeCast assumes that content is encoded using a Reed-Solomon encoding mechanism. Reed-Solomon Codes (RSC) [22] are a popular FEC coding technique, which is used in many FEC-based reliable multicast protocols [17, 28]. RSCs are based on the arithmetic of finite (Galois) fields [27]. RSC-like codes have been proposed and used in a number of projects for efficient information retrieval. Examples include (1) the Information Dispersal Algorithm (IDA) [26] used for efficient, secure, and fault-tolerant parallel data access [20], (2) the Adaptive IDA protocol [4] used in TCP Boston to address the fragmentation of IP over ATM [5], and (3) the Tornado codes [19] used in Digital-Fountain multicast [6].

The SomeCast paradigm is *independent* of the specific Reed-Solomon coding technique chosen for an implementation. However, to make our presentation concrete—and for purposes of illustration and derivation of specific realizations—we will adopt one such coding technique, namely the Information Dispersal Algorithm (IDA) of Rabin [26].[3] To understand how IDA works, consider (a segment of) a data object to be multicast. Let that object consist of K *blocks* (or packets). Using IDA's *dispersal operation*, this object could be processed to obtain $s \times K$ blocks, where $s > 1$ is the *stretch factor*. Recombining *any* K of these blocks, using IDA's *reconstruction operation*, is sufficient to retrieve the original data object. Figure 2 illustrates data dispersal, communication, and reconstruction using IDA.

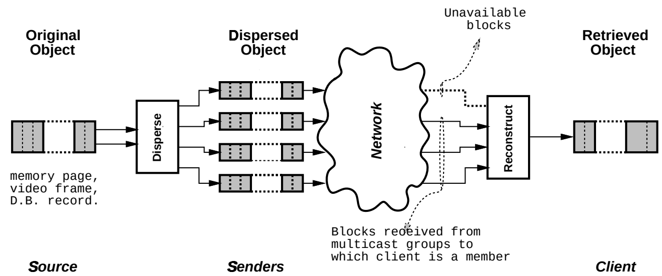


Figure 2. IDA Dispersal and reconstruction.

4. RT Reliable Multicast using SomeCast

In this section, we present an instance of a SomeCast-enabled protocol that empowers a set of receivers to satisfy diverse RT QoS constraints in a reliable multicast setting. Consider the reliable multicast of an object of size K packets. We assume that the object is encoded so that each sender S_i has $u \times K$ packets, where $u = s/\mathcal{S}$, s is the stretch factor of the encoding and $\mathcal{S}$ is the total number of senders. S_i starts a multicast group over which its packets will be sent only if there is at least one receiver that is a member of its group. At any point in time, if S_i finds that its group is empty (i.e., with no members), S_i stops transmitting packets.

Let S_0 be the primary sender. If there is no deadline requirements or the delay bounds are very loose, then a receiver may only join the multicast group of S_0 to receive at least K packets and reliably recover the original data by the deadline. Initially, a receiver may join one or more multicast groups associated with one or more senders. Those senders send packets over their multicast groups. By allowing a receiver to join all groups, the protocol can effectively handle stringent delay bounds. For less stringent delay bounds, the receiver may leave all but the first group associated with the primary sender S_0. Peri-

[3]Other Reed-Solomon-like coding techniques (e.g. Tornado [19]) may have more attractive properties than those of IDA with respect to encoding and decoding efficiency (for example). Thus, if SomeCast is to be deployed, IDA may not be the best choice. For the purposes of this paper, IDA's elegance and simplicity will allow us to focus on the details of the SomeCast paradigm as opposed to the details of the underlying encoding/decoding technology.

Symbol	Meaning
K	Number of original data packets. Each receiver should receive K packets by the deadline.
$\mathcal{S}$	Total number of senders.
S_i	Sender S_i.
s	Stretch factor of the Reed-Solomon-like encoding. The K original data packets are encoded to obtain up to $s \times K$ packets.
$u \times K$	Maximum number of packets transmitted by a sender, where $u = s/\mathcal{S}$. We take $u = 2$.
$maxseqno_i$	Maximum sequence # of data to be transmitted by S_i.
$seqno_i$	Sequence # of packet (probe) sent by/received from S_i.
PTS_i	Number of packets yet-to-be-transmitted at the time S_i sends a probe.
RPC_i	The Received Packet Counter denotes the number of packets received thus far from S_i.
$TRPC$	The Total Received Packet Counter denotes the number of packets received thus far.
g	Current number of groups to which a receiver is subscribed.
D	A receiver's deadline.
R_i	Estimated throughput from S_i.
L_i	Estimated loss rate on the path from S_i.
RTT	Maximum Round-Trip Time between the sender and a receiver.
$expPkts_i$	Expected number of packets received by the deadline from S_i.

Table 1. SomeCast-enabled protocol (Notation)

odically, a receiver updates its estimates of its loss rate and throughput of the path from sender S_i. A receiver can then estimate the total number of packets that it *expects* to receive by the deadline from senders/groups to which it is subscribed. If this is not enough to receive all K packets by the deadline, then the receiver joins as many groups as needed. On the other hand, if the receiver anticipates to receive *much* more than K packets by the deadline, then the receiver unsubscribes from "some" groups to only receive what is needed and thus avoid unnecessary transmissions. Without loss of generality, we henceforth assume that if a receiver decides to unsubscribe from some multicast groups, it does so by unsubscribing from higher numbered ones first.

In addition to dynamically adjusting the number of groups to which a receiver subscribes, in response to probes from senders, a receiver sends sender S_i NACK messages specifying how many more packets it needs from S_i. Thus, S_i can send the right amount of additional packets so that all receivers subscribed to its group meet their deadlines. Whenever a receiver receives K packets, it leaves all multicast groups to which it is currently subscribed.

Protocol Description: Table 1 introduces the notation we adopt throughout this paper to describe our SomeCast-enabled protocol. We describe our SomeCast-enabled protocol by presenting the steps undertaken by the Sender(s) and Receiver(s) at various stages of the protocol.

Sender: Start

SS.1 Each sender S_i ($i = 0, 1, \cdots, \mathcal{S} - 1$) sets the initial $seqno_i$ of its first packet and its $maxseqno_i$.

$$seqno_i = 2iK \quad ; \quad maxseqno_i = 2iK + K - 1$$

SS.2 If sender has receivers in its multicast group, it starts to transfer the first K data packets.

SS.3 Concurrently with step SS.2,[4] the sender applies coding to the first K data packets to obtain $2K$ packets.

Sender: Probing

SP.1 Periodically, a sender transmits a probe piggybacked on a data packet. The probe consists of a timestamp that identifies the time at which the probe is sent and PTS_i. Namely, $PTS_i = maxseqno_i - seqno_i$, where $seqno_i$ is the sequence number of the packet transmitted with the probe.

Sender: NACK Processing

SN.1 Upon receipt of a NACK, sender S_i updates $maxseqno_i$ to the *maximum* requested by all receivers in response to the same probe. This ensures that all receivers subscribed to the multicast group of S_i receive the additional packets they need by their deadlines.

SN.2 Upon receipt of a NACK, sender S_i also updates its estimate of the maximum Round Trip Time (RTT).

SN.3 While transmitting the last RTT worth of packets, sender ignores NACK requests for decreasing $maxseqno_i$ to avoid errors due to possible underestimation of losses in the last stage.

Sender: End

SE.1 Sender S_i stops its transmission once all members (receivers) in its group leave.

Receiver: Packet Processing

RP.1 Whenever a receiver receives a packet from sender S_i, it increments the Received Packet Counter (RPC_i). Also, it increments the Total Received Packet Counter ($TRPC$).

RP.2 If $TRPC$ is greater than or equal to K, the original data can be reconstructed from the packets received so far. The receiver then decodes the received data and leaves all multicast groups it is a member of.[5] If the

[4] Our protocol may overlap data transmission with encoding/decoding, hence dramatically reducing latency for all receivers to receive the number of packets needed for recovering the original data by the deadline.

[5] By allowing receivers to leave multicast groups once they receive the K packets needed, we significantly reduce the bandwidth consumed over the network.

deadline has expired, the receiver drops all (useless) packets it has received so far and leaves all multicast groups it is a member of.

RP.3 If $TRPC$ is less than K and if the packet received is a probe, then the receiver proceeds as follows:

RP.3.1 If ($seqno_i + PTS_i < maxseqno_i$ of receiver), then the forthcoming packets from S_i are not enough to recover the original data. The receiver sends a NACK that includes the new lower bound on $maxseqno_i$ calculated in step RE.4.

RP.3.2 If ($seqno_i + PTS_i \geq maxseqno_i$ of receiver) and ($seqno_i + PTS_i$) equals a $maxseqno_i$ the receiver had sent to S_i in a previous NACK, then the receiver was the bottleneck and is now uneccessarily requiring S_i to send more packets than needed. The receiver sends a NACK that includes the new lower $maxseqno_i$ calculated in step RE.4.

Receiver: Periodic Estimation

RE.1 Periodically, a receiver updates its loss rate estimate l_i on the path from sender S_i to which it is subscribed.[6]

$$l_i = 1 - (\Delta RPC_i / \Delta seqno_i)$$

where $\Delta seqno_i$ is the difference in sequence numbers of packets received from sender S_i at the beginning and end of the update time interval. ΔRPC_i is the number of packets received from S_i during the update interval. Thus, the ratio l_i gives the current proportion of S_i packets lost.

RE.2 Periodically, a receiver updates its throughput r_i from sender S_i, namely $r_i = \Delta RPC_i / \Delta t$, where Δt is the length of the update interval.

RE.3 Based on l_i and r_i, a receiver maintains exponential moving averages and deviations of the loss rate and throughput for each sender S_i. Specifically,

$$\begin{aligned} AvgR_i &= \alpha\, AvgR_i + (1-\alpha)\, r_i \\ DevR_i &= (1-\delta)\ |\, r_i - AvgR_i \,| + \delta\, DevR_i \\ R_i &= AvgR_i + \gamma\, DevR_i \end{aligned}$$

where R_i is the estimated throughput from sender S_i. $AvgR_i$ and $DevR_i$ are the moving average and deviation, respectively.[7] Similarly, the loss rate L_i from sender S_i is estimated.

RE.4 Compute $maxseqno_i$ for each sender S_i the receiver is listening to (*i.e.*, receiver is currently a member of S_i's multicast group) based on R_i and L_i computed as in RE.3

$$maxseqno_i = \min(seqno_i + \frac{R_i}{1-L_i} \times (D-t),\ 2\,(i+1)\,K - 1)$$

where $seqno_i$ is the most recent sequence number from sender S_i received at time t, and D is the receiver's deadline. Thus, the term $\frac{R_i}{1-L_i} \times (D-t)$ represents the number of *additional* packets S_i needs to send so that the receiver receives the number of packets it expects from S_i by the deadline D. Note that $maxseqno_i$ cannot exceed $(2\,(i+1)\,K - 1)$ since each sender is assumed to hold $2K$ encoded packets.

RE.5 For each sender S_i, estimate the expected number of packets, $expPkts_i$, to be received by the deadline. If $maxseqno_i$ for S_i is set as the maximum encoded number, i.e., $(2(i+1)K-1)$, as in RE.4, then $expPkts_i$ is

$$expPkts_i = (maxseqno_i - seqno_i) \times (1 - L_i)$$

Otherwise, $maxseqno_i$ is calculated by $seqno_i + \frac{R_i}{1-L_i} \times (D-t)$, so $expPkts_i$ is

$$expPkts_i = R_i \times (D-t)$$

RE.6 Estimate the total number of packets, N_j, expected from all senders by the deadline.

$$N_j = TRPC + \sum_{i=0}^{j-1} expPkts_i$$

where j ranges from 1 to g (the current number of groups to which the receiver is subscribed), $expPkts_i$ is computed as in RE.5. The first term represents the number of packets already received, and the second term represents the number of packets that the receiver *anticipates* to receive by the deadline. For each j from 1 to g, N_j is calculated and compared with K. If N_j is greater than K, then set the proper number of groups to join as j.

RE.7 The receiver decides whether it should join or leave multicast groups based on the proper number of groups computed in RE.6. If this number is greater than the current number, g, then the receiver joins sender S_{g+1}, where $g+1$ is less than and equal to maximum number of senders in the network. On the other hand, if the proper number of groups is less than g and N_j exceeds $K + relax$, where $relax$ is a protocol parameter[8] chosen to ensure that N_j is well beyond K, then the receiver unsubscribes from groups numbered higher than j.

Sender Probing and RTT Estimation

During data transmission, sender S_i transmits probes periodically. A probe packet includes the number of packets to be sent (PTS_i) and time-stamp for when the packet is sent. The purpose of using probes is two-fold: First, a probe is used to trigger NACKs from receivers. Upon receiving the probe containing PTS_i, a receiver makes a local decision whether this is enough to sustain its current loss rate as we described earlier in RP.3. Second, a probe is used to estimate the round-trip time (RTT).

[6] In our experiments, and unless otherwise specified, we take the update period to be 0.2 seconds.

[7] In our experiments, we take $\alpha = \delta = 0.5$, and we set γ to 1. γ could be set to higher values to account for high variability in the case of stringent deadlines.

[8] In our experiments, we take $relax$ to be 20 packets for $K = 1000$ packets.

When a receiver responds with a NACK, it sends the time-stamp for when the NACK is sent. The time-stamps are used to calculate RTT as suggested in [23]: the sender sends a probe at time t_1, and a receiver receives the probe at time t_2. If the receiver sends a NACK at time t_3, it includes (t_1, Δ), where $\Delta = t_3 - t_2$. Once the sender receives the NACK at time t_4, it computes RTT as $RTT = t_4 - t_1 - \Delta$.

In other reliable multicast protocols such as SRM [14] and SHARQFEC [17], the estimation of RTT is very critical for NACK suppression and repair. However, in our protocol, the RTT value is not critical. The sender only needs an estimate of the maximum RTT from receivers to set the probing period. As more data is transmitted, the feedback from receivers about their losses in response to probes becomes more critical. Thus, it is desirable to gradually decrease the probing period (to no less than the RTT to avoid sending duplicate probes).[9]

SomeCast Extensions

Due to space limitations, we do not present results of SomeCast extensions for the dynamic selection of the "best set of server(s)" by a receiver, for balancing load across servers, and for a TCP-friendly transmission by the servers. Here, we briefly discuss such extensions.

To enable receivers to *choose* the subset of multicast groups to which they subscribe, we have evaluated novel *multicast group selection* algorithms, which take into consideration knowledge of static network topology (e.g. based on distance between receiver and sender or closest router carrying the multicast group) or dynamic network conditions (e.g. whether or not paths to two multicast groups share a common congestion).

One of the salient features of the SomeCast paradigm is that it delegates the responsibility of QoS management to receivers. As we indicated earlier, such delegation is attractive because it boosts the scalability of the system by making the overhead incurred by senders *independent* of the number of receivers and/or the diverse characteristics of paths between senders and receivers. Another advantage of delagating the management of real-time QoS constraints to receivers is that it enables senders to respond to network congestion conditions without risking the violation of QoS constraints at the receivers (since receivers can recover from a reduction in the rate at which a sender transmits data on its multicast group). We have investigated such techniques, whereby SomeCast senders manage congestion by adopting TCP-friendly transmission policies (as opposed to the constant-bit-rate policy we adopted in the implementation presented in this paper).

[9] In our simulations, sender S_i sends the first probe after sending the first $K/5$ packets, then the probing frequency is increased by sending one probe every RTT.

5. Performance Evaluation

Simulation Model: To evaluate the performance of SomeCast against that of Unicast and ManyCast, we set up a simulated multicast network using the 19-node tree topology depicted in Figure 3. In this topology, a CBR (Constant Bit Rate) data source is attached to each of nodes 14 to 18 (the primary sender S_0 is attached to node 14). All other nodes (i.e. nodes 0 to 13) act as receivers. The packet interarrival time for the CBR source is set to 0.01 second. Each link in the network is subjected to a maximum of 32 on-off cross connections generated by a UDP-based agent. This UDP-based agent generates connections with an inter-arrival time uniformly distributed between 0 and 0.1 second. Each connection is an on-off source with Pareto distributed "on" and "off" periods with average durations of 0.1 second and 0.9 second, respectively. The Pareto distribution has a skew parameter of 1.35. During the "on" periods, packets are generated at a rate of 1000Kbps. This cross-traffic resulted in up to 30% loss rates observed at receivers. The bandwidth of the links in our simulated topology are set to 1.5Mbps. All links have a propagation delay of 15ms. The packet size is 1KB. We take $K = 1000$ packets, so the size of the data is 1MB.

ns Prototype Implementations: We prototyped an implementation of our SomeCast-enabled protocol using the UCB/LBNL/VINT network simulator, ns-2.1b4 [24]. A new agent, called *scast*, is created as a subclass of AgentClass and defined in `scast.cc` and `scast.h`. This agent implements the SomeCast-enabled protocol. The primary sender starts transmitting data at time 25.0 (a warm-up period during which cross traffic at all links are generated). Other senders start transmitting as soon as one or more receivers join their multicast groups. The simulation run is stopped once *all* receivers receive by the deadline the needed packets to recover the original data, or whenever the simulation clock exceeds the deadline. In the latter case, one or more receivers had missed their deadline.

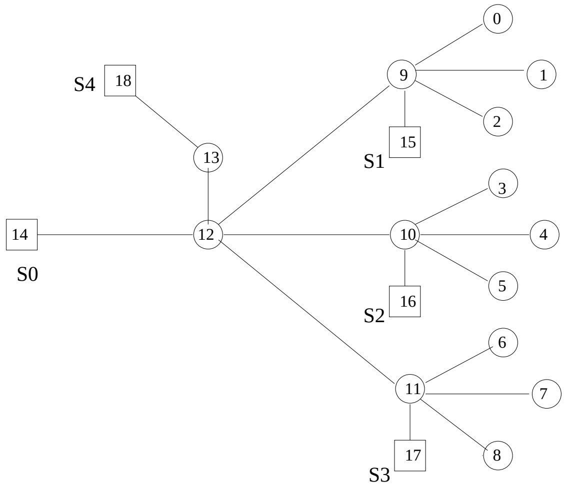


Figure 3. Topology used in our simulations

In our experiments, we take the total number of senders/groups to be 5. Each sender is assumed to have $2K$ encoded packets. We consider two variations of our protocol: (1) **SomeCast-1** where a receiver starts by joining the multicast group of primary sender S_0 and then joins other groups as needed; and (2) **SomeCast-5** where a receiver starts by joining all multicast groups of all 5 senders and then leaves groups as needed as long as it is able to receive by the deadline the number of packets it needs for full recovery.

To compare against SomeCast, we also simulated the two special cases of **ManyCast** and **UniCast**. ManyCast is the same as SomeCast except that joins and leaves are static, i.e. every receiver is subscribed to all multicast groups all the time. In Unicast, there is only one sender, the primary one, that every receiver joins.

Performance Metrics: To compare SomeCast to the ManyCast and UniCast based protocols, we considered the following performance metrics:

- *Guaranteed Deadline Percentage:* Percentage of receivers which successfully receive by the deadline (D) all packets (K) needed for full recovery.
- *Goodput:* Ratio of number of packets received and used for data reconstruction (by all receivers) to the number of packets sent (by all senders).
- *Average Number of Groups Joined:* Average number of multicast groups that a receiver joins.

In our simulations, we assume (for simplicity) that all receivers are subject to the same deadline. We define the *laxity* to be the ratio between the requested deadline and the most stringent deadline that can be met (i.e. when there are no losses and when every receiver joins the multicast groups of all 5 senders).

Simulation Results: We present our performance metrics as a function of laxity. Figure 4 shows the Percentage of Guaranteed Deadlines, the Goodput, and the Average Number of Groups Joined.

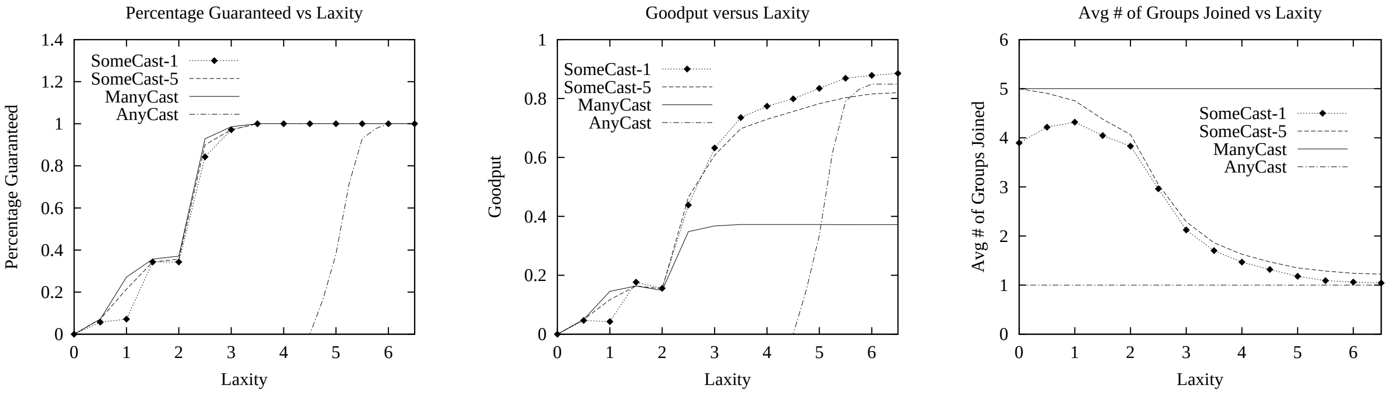
Since in our SomeCast protocol, a receiver adjusts dynamically the number of groups to which it subscribes, SomeCast strikes a good balance between Percentage Guaranteed and Goodput since a receiver joins the *minimum* number of groups needed to receive K packets by the deadline. UniCast, where every receiver only joins the primary sender, yields the lowest Percentage Guaranteed and Goodput for a wide range of laxity values. Finally, ManyCast, where every receiver joins all 5 groups, yields the highest Percentage Guaranteed at the expense of lower Goodput.

It is important to note that at lower laxities, ManyCast has the highest Goodput as it is able to make use of transmissions from all 5 senders to satisfy the requested deadline at many receivers. Other protocols suffer from lower Goodput as many receivers fail to meet their deadlines and transmissions, albeit from fewer senders, are wasted. Figure 4(c) illustrates how a SomeCast receiver adapts the number of multicast groups to which it subscribes depending on how stringent the deadline is.

Observe that the performance of SomeCast approaches that of UniCast under high laxities, and that of ManyCast under low laxities. Note the system is non-linear—as laxity increases beyond 2 seconds, performance in terms of Percentage Guaranteed and Goodput sharply increases as it becomes possible for several receivers to meet their deadlines.[10] This behavior is typical of real-time systems.

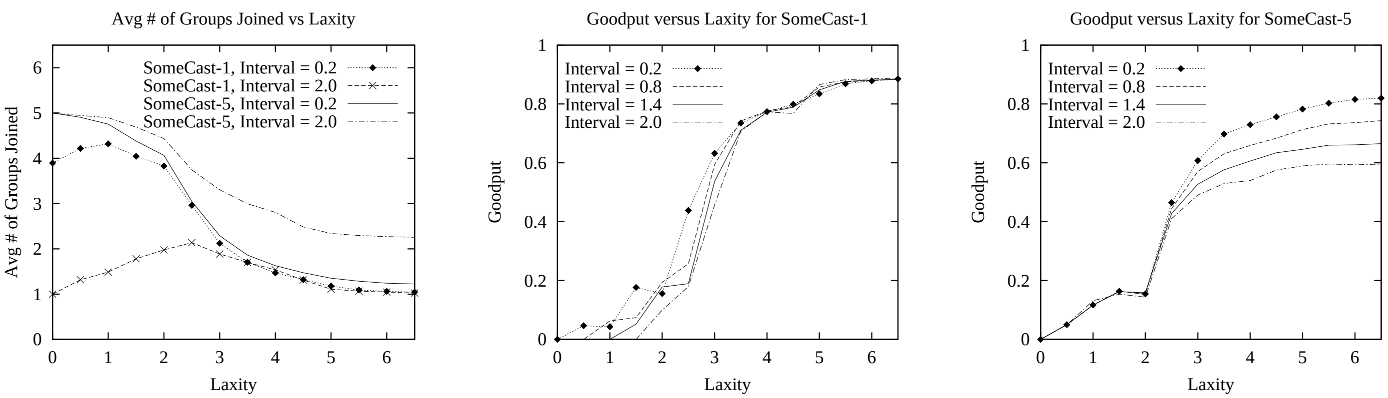
Figure 5 shows the behavior of SomeCast-1 and SomeCast-5, respectively, for varying receiver update intervals. Recall from Section 4 that the update interval dictates how frequently a receiver updates its estimates of loss rate and throughput of its path from each sender, which then allows the receiver to decide whether to join groups of additional senders or leave some groups to which it is currently subscribed. Clearly, more frequent updates allow the receiver to adjust its level of service in a more timely fashion at the expense of higher com-

[10] This is an artifact of the specific topology and link delays used in our simulations.



(a) (b) (c)

Figure 4. Performance vs. Laxity: (a) Guaranteed Deadlines %, (b) Goodput, and (c) Average # of Groups.



(a) (b) (c)

Figure 5. Groups joined (a) and effect on Goodput vs. Laxity in SomeCast-1 (b) and SomeCast-5 (c).

putational overhead. In SomeCast-1, more frequent updates are more critical at lower laxities so as to allow the receiver to *join* more senders in a timely fashion, hence increasing Goodput (cf. Figures 5(a) and (b)).[11] In SomeCast-5, more frequent updates are more critical at higher laxities so as to allow the receiver to *leave* in a timely fashion additional senders beyond what is needed to fully recover the data by the (loose) deadline. These more frequent updates result in higher Goodput (cf. Figures 5(a) and (c)).[12] These results suggest a dynamic update policy where the frequency of updates is dependent on how stringent the requested deadline is.

[11]Not shown is Percentage Guaranteed, which is also higher with more frequent updates.

[12]Not shown is Percentage Guaranteed, which is not much affected by the frequency of updates in SomeCast-5.

6. Summary

We have proposed SomeCast—a novel paradigm for the reliable multicast of real-time data to a large set of receivers over the Internet. SomeCast is *receiver-initiated* and thus scalable in the number of receivers, the diverse characteristics of paths between senders and receivers, and the dynamic conditions of such paths. SomeCast enables receivers to adapt dynamically to the unpredictability of network conditions. This adaptation enables receivers to meet specific real-time QoS constraints. We have presented an instance of a SomeCast-enabled protocol, which we have prototyped under the UCB/LBNL/VINT network simulator (ns-2.1b4). We have presented simulation results that show the superiority of SomeCast when compared to the previously proposed ManyCast and AnyCast paradigms.

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