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AIDA: A Bandwidth Allocation Strategy for Distributed Real-Time Systems

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Abstract

In this paper, we propose a superior technique for distributed time-critical communication using AIDA, a novel elaboration on Michael O. Rabin's IDA [19]. We show that using a small *dynamically-controlled* amount of redundancy, stringent timing constraints imposed on periodic as well as sporadic communication requests in a distributed real-time system can be fulfilled up to any degree of confidence. AIDA is *randomized* in the sense that it does not guarantee the fulfillment of hard time constraints. Instead, it guarantees a lower bound on the *probability* of fulfilling such constraints. We contrast AIDA with traditional communication scheduling techniques used in conjunction with time-critical applications in general, and distributed multimedia systems in particular. The suitability of AIDA-based bandwidth allocation for a variety of time-critical applications is established and plans for future research experiments are mentioned.

1 Introduction

The successful execution of a time-critical task running in a distributed environment often requires that a set of communication transactions (*e.g.* fetching a number of pages from a set of remote sites) be successfully completed before a set deadline. In order to guarantee such conditions, an accurate knowledge of the delays introduced by the communication network is often required. For communication scheduling purposes (hereinafter referred to as *bandwidth allocation*), such knowledge can be acquired either statically or dynamically. Using static techniques, worst-case delays are determined and accounted for *a priori*. Alternatively, using dynamic techniques the average (or maximum) delays experienced through a communication network can be measured and used as an *estimate* for use with future communication transactions. Static communication scheduling (using a priori knowledge about the communication network delays) can be safely and efficiently used in systems with predetermined communication patterns (*e.g.* broadcasting) and systems with predetermined computation requirements (*e.g.* periodic tasks). For systems with unpredictable communication patterns or systems with sporadic computation requirements, dynamic communication scheduling becomes necessary.

Several techniques have been suggested in the literature for dynamic bandwidth allocation. Most of these techniques rely on the use of feedback from the communication network to establish a performance model that can be used in conjunction with a scheduling algorithm to allocate/reserve the communication bandwidth needed for the successful execution of time-critical tasks [15, 17].

While bandwidth allocation is an important consideration in the design of distributed time-critical systems (such as multimedia), it is not the only one. Issues of reliability, availability, and fault-tolerance are equally (if not more) important. The most common technique used to tackle these issues is *replication*. For example, in distributed database applications [2, 7], several copies of a particular data object might be kept in a number of different sites so that the failure (whether intermittent or permanent [20]) of any proper subset of these sites would not render the data object unavailable. For distributed applications operating under strict time constraints, replication alone might not be sufficient. In particular, failures should not be allowed to increase the retrieval delay for data objects (at least not considerably). In this respect, techniques that rely on watchdog timers and/or retransmit protocols

may not be adequate. Instead, techniques that use redundant communication (*e.g.* , requesting the same data object from a set of failure-independent sites/paths) might be necessary. This, however, might have an adverse impact on the overall performance of the system due to the added "redundant" communication traffic.

In this paper we propose AIDA (Adaptive Information Dispersal Algorithm), a novel technique for dynamic bandwidth allocation, which makes use of minimal, controlled redundancy to guarantee timeliness and fault-tolerance up to any degree of confidence. Our technique is an elaboration on the Information Dispersal Algorithm of Michael O. Rabin [19], which we have previously shown to be a sound mechanism that considerably improves the performance of I/O systems and parallel/distributed storage devices [3, 6].

2 Real-time Bandwidth Allocation: Related work

One way to schedule data transmission is to maintain statistics characterizing each of the communication resources (channels) in the system. Whenever the channel characteristics of the network change, the server responsible for delivering the time-critical data can adjust accordingly to maintain predictable service. This can be achieved by decreasing the demand on the network. For example, when a network becomes congested and the percentage of late data elements (missed deadlines) increases, dropping the demand on the network helps clear the congestion [12]. This effectively allows data elements scheduled for transmission to traverse the communication network and reach their destination *on time* rather than be lost due to lateness.

Another mechanism to deal with the adverse effect of network congestion is to distinguish between the various communication requirements. This was proposed in the Asynchronous Timesharing System (ATS) [15], in which data traffic is divided into four classes. A control class C has the highest priority; it delineates a class of communication where data loss or unpredictable communication delays cannot be tolerated. Class I is next on the priority scale; it delineates a class of communication where data loss cannot be tolerated, but a user-specified maximum end-to-end communication delay is allowed. Class II has a set maximum percent of lost packets and a maximum count of consecutive packets lost. Finally, class III has zero loss and no maximum end-to-end delay for communication that is not subject to time constraints. A similar treatment of the different communication requirements imposed on a distributed system is under investigation at the University of California at Berkeley, where an experimental RAID-II network file server is being implemented [16].

The network protocol presented in [9, 8] handles performance requirements in a different manner. When a connection is requested, the user provides the network manager with maximum end-to-end delay, maximum packet size, maximum packet loss rate, minimum packet inter-arrival time, and maximum jitter, where jitter is defined as the difference in the delays experienced between two packets on the same connection. Three types of channels can be requested: *deterministic, statistical,* and *best-effort.* For deterministic channels, the communication delay is guaranteed to fall below a given time bound. For statistical channels, the probability that the delay is less than a given time D is kept greater than or equal to a requested factor q. This can be thought of as establishing a *confidence interval* about the expected delay rather than a *deterministic bound* on that delay. Best-effort channels provide no guarantees for the percentage of messages reaching their destination on-time; they merely attempt to make the best use of the available bandwidth.[1]

Statistical approaches to overcoming delay and bandwidth limitations are attractive because they provide application programs with a flexible framework, in which a continuum of communication priorities can be easily expressed as confidence intervals. In particular, we argue that the distinction between deterministic, statistical, and best-effort channels in the protocol proposed in [9, 8] is artificial. Deterministic and best-effort channels can be thought of as *special* statistical channels, for which

[1] Deterministic channels are necessary for computations with *hard* time constraints, whereas statistical channels are appropriate for computations with *soft* time constraints. Best-effort channels are adequate for computations with no time constraints.

the confidence interval (determined by q) describing the communication delay is taken to its limits.[2] Therefore, in this paper (without loss of generality), we consider only statistical channels.

Current techniques for statistical bandwidth allocation [18] rely on choosing an end-to-end time delay T per packet that is larger than the delay expected to be experienced by a percentage P of the retrieved packets. This time T is used as an estimate for the time it will take to retrieve packets from a given source. While such a delay function can accurately represent delay characteristics over a given period of time, network loading does change with time, possibly making the delay distribution (and thus the delay function) outdated. One way to accommodate this dynamic behavior is to monitor the delays experienced by retrieved packets and adjust the delay function accordingly. In [10], a mechanism called *Limited A Priori* (LAP) scheduling is proposed, in which adjustments to the delay function are made either periodically or whenever sudden changes in network traffic are detected. Using second and higher order moments, linear and quadratic extrapolation of the network delay characteristics can be more accurately predicted.

All of the bandwidth allocation mechanisms described so far (with the exception of RAID-II) assume a single source of data for a given transaction. In a truly distributed environment, this is not likely to be the case. The storage of a single object might span a number of nodes, either because of fault-tolerance requirements[3] or else to accommodate data placement constraints. Although it is possible to extend the aforementioned bandwidth allocation mechanisms to deal with data distributed over a number of nodes, the performance of these protocols deteriorates significantly. The mechanism we are proposing in this paper is inherently distributed and, in that respect, is far more superior.

3 Information Dispersal and Retrieval Using IDA

In this section we overview the original Information Dispersal Algorithm (IDA). We refer the reader to the original paper on IDA [19] for a more thorough presentation.

Let F represent the original data object (hereinafter referred to as the *file*) in question. Furthermore, let's assume that the storage of file F is to be distributed over N sites. Using the IDA algorithm, the file F will be processed to obtain N distinct pieces in such a way that recombining *any* m of these pieces, $m \leq N$, is sufficient to retrieve F. The process of processing F and distributing it over N sites is called the *dispersal* of F, whereas the process of retrieving F by collecting m of its pieces is called the *reconstruction* of F.

Figure 1 illustrates the dispersal and reconstruction of an object using IDA. The dispersal and reconstruction operations are simple linear transformations using *irreducible polynomial arithmetic.*[4] Both the dispersal and reconstruction of information using IDA can be performed in real-time. This was demonstrated in [4], where we presented an architecture and a CMOS implementation of a VLSI chip[5] that implements IDA.

Let $|F|$ be the size of the file F. The IDA approach *inflates* F by a factor of $\frac{N}{m}$. In particular, the size of each one of the dispersed pieces of F would be $\frac{|F|}{m}$. This added redundancy makes the system capable of tolerating up to $N-m$ faults without any effect on timeliness. More importantly (as we will demonstrate shortly), this added redundancy will boost the performance of the information retrieval process *significantly.*

Several *redundancy-injecting* protocols have been suggested in the literature to deal with fault-tolerance issues. In most of these protocols, redundancy is injected in the form of parity blocks, which

[2] For deterministic channels, $q = 1$. For best-effort channels, $q = 0$.

[3] For example, striping data for a video presentation over N nodes would increase the *availability* of the system by allowing a graceful degradation of the quality of the presentation by $1/N\%$, should any of the N nodes fail.

[4] For a concrete implementation and for examples, the reader is referred to our previous work on SETH [4] and IDA-based RAID I/O systems [5].

[5] The chip (called SETH) has been fabricated by MOSIS and tested in the VLSI lab of Harvard University, Cambridge, MA. The performance of the chip was measured to be about 1 megabyte per second. By using proper pipelining and more elaborate designs, this figure can be boosted significantly.

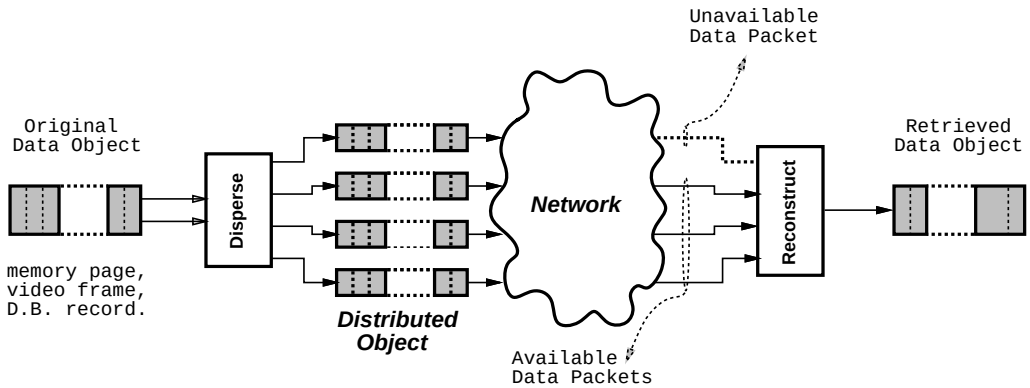

Figure 1: Dispersal and reconstruction of information using IDA.

are only used for error detection and/or correction purposes [11]. The IDA approach is radically different in that redundancy is added *uniformly*; there is simply *no* distinction between data and parity. It is this feature that makes it possible for IDA to be used not only to boost communication fault-tolerance, but also to improve bandwidth allocation and utilization.

An important aspect of IDA, unlike other redundancy-injecting protocols [21, 16], is that the amount of redundancy to be used with a given object, or in a given communication session, does *not* have to be constant. In particular, our AIDA-based bandwidth allocation strategy *controls* the amount of redundancy to be used with a particular object in a particular communication session so as to reflect the *priority* and/or the *urgency* of the transaction at hand. By increasing the redundancy allocated for a given communication session, the expected retrieval delay can be reduced, thus increasing the chances of meeting the possibly tight time constraint imposed on the transaction.

4 Performance Characteristics

Let X be a data object dispersed using IDA into N pieces, each residing in a different site. Let m be the minimum number of pieces needed to reconstruct X. Obviously, in order to retrieve X, at least m of the N sites must be consulted. It is possible, however, to consult more than m of these sites. Let n (where $m \leq n \leq N$) denote the total number of sites *consulted* for the retrieval of X. In this section, we derive an expression for the expected communication delay for accessing such an object. Later, we will use this result to establish the merits of our proposed AIDA-based bandwidth allocation protocol.

$$\begin{aligned} \text{Prob}(t \geq z) &= \text{Prob(Response time of at least } (n-m) \text{ of the sites} \geq z) \\ &= \sum_{r=n-m+1}^{n} \binom{n}{r} P^r (1-P)^{n-r} \end{aligned} \tag{1}$$

where P is the probability that the response time of a single site will be z or more. P can be estimated using delay characteristic functions or approximation thereof.

4.1 Approximation using a uniform distribution delay model

As a first and safe approximation, we will assume that the delays experienced through the communication network are *uniformly distributed* random variables with lower and upper bounds ($D_{\min}$ and $D_{\max}$) as illustrated in figure 2. Let P_u be the value of P (in equation 1) under this assumption.

$$P_u = \begin{cases} 1 & \text{if } \quad 0 < z < D_{\min} \\ 1 - \frac{z - D_{\min}}{D_{\max} - D_{\min}} & \text{if } D_{\min} \leq z \leq D_{\max} \\ 0 & \text{if } D_{\max} < z < \infty \end{cases}$$

The random variable t (in equation 1) is simply the $(n-m+1)^{\text{th}}$ largest of these n uniformly distributed independent random variables. It can be shown that t follows the *beta probability law* and that the mean and standard deviation for t are given by:[6]

$$\tau_u = D_{\min} + \frac{m}{n+1}(D_{\max} - D_{\min}) \tag{2}$$

$$\sigma_u = \sqrt{\frac{m(n-m+1)}{(n+1)^2(n+2)}}\,(D_{\max} - D_{\min}) \tag{3}$$

4.2 Approximation using an exponential distribution delay model

We denote by P_e the value of P (in equation 1) under the exponential distribution delay model.

$$P_e = \begin{cases} 1 & \text{if} \quad 0 < z < D_{\min} \\ e^{-\lambda(z - D_{\min})} & \text{if } D_{\min} < z < \infty \end{cases}$$

Let τ_e denote the average delay experienced using an IDA-based strategy under an exponential distribution delay model with parameter λ (see figure 3). To compute τ_e, we need to compute the *mean* value of the random variable t. This can be done as follows:

$$\begin{aligned}
\tau_e &= \text{Expected delay under an exponential distribution assumption} \\
&= D_{\min} + \int_{D_{\min}}^{\infty} \text{Prob}(t \geq z) \cdot dz \\
&= D_{\min} + \sum_{r=n-m+1}^{n} \binom{n}{r} \int_{D_{\min}}^{\infty} P^r (1-P)^{n-r} \cdot dz \\
\tau_e &= D_{\min} + \sum_{r=n-m+1}^{n} \binom{n}{r} \int_{0}^{1} P^r (1-P)^{n-r} \cdot \frac{1}{\lambda P} \cdot dP \\
&= D_{\min} + \frac{1}{\lambda} \sum_{r=n-m+1}^{n} \frac{\Gamma(n+1)}{\Gamma(r+1)\Gamma(n-r+1)} \frac{\Gamma(r)\Gamma(n-r+1)}{\Gamma(n+1)} \\
\tau_e &= D_{\min} + \frac{1}{\lambda} \sum_{r=n-m+1}^{n} \frac{1}{r} \qquad (4)
\end{aligned}$$

Unless stated otherwise, the remainder of this paper assumes an exponential delay model.

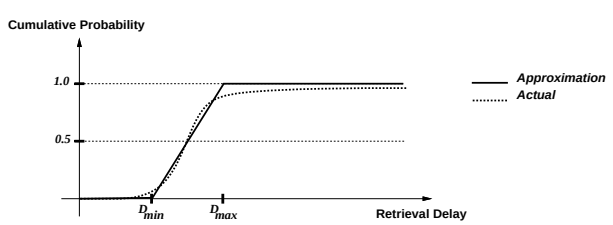

Figure 2: Uniform delay assumption

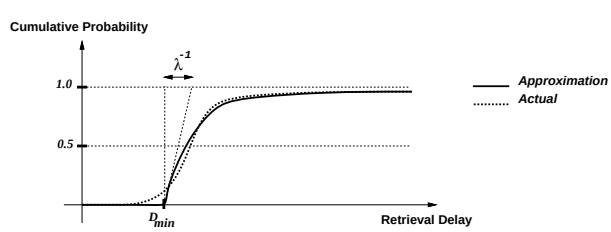

Figure 3: Exponential delay assumption

[6] Derivation is omitted for space limitations. For a reference, refer to [14].

4.3 Effect of distribution and redundancy on delay characteristics

There are a number of interesting observations to be made from the delay analysis of the previous section. By varying the values of n and m, the negative effect of data distribution and the positive effect of data redundancy on the delay characteristics can be demonstrated. The following cases can be readily examined:

a. $\underline{n = m = 1}$: This is the case when the object X is not distributed. The expected delay reduces to $\frac{1}{2}(D_{\min} + D_{\max})$ under the uniform delay model and reduces to $D_{\min} + \frac{1}{\lambda}$ under the exponential delay model. This corresponds to the average delay for one transmission.

b. $\underline{n > m = 1}$: This is the case when the object X is replicated over n sites. For $n \gg 1$, the expected delay approaches $D_{\min}$, which is the minimum delay for one transmission under both the uniform and exponential delay models.

c. $\underline{n = m > 1}$: This is the case when the object X is distributed with no added redundancy. For $n \gg 1$, the expected delay approaches $D_{\max}$, which is the maximum delay for one transmission under the uniform delay model. Under the exponential delay model, it approaches $D_{\min} + \frac{1}{\lambda}\ln(n)$, making the communication delay logarithmically proportional to the distribution level.

IDA-based communication attempts at striking a balance between the above three extreme setups. Figure 4 illustrates the improvement (speedup) in communication delay that can be achieved through the use of even remarkably small levels of redundancy.[7] For example, at a 20% redundancy level ($\frac{1}{5}$ of the communicated data is redundant), IDA cuts the expected delay through a communication network by almost 50% (a 2-fold speedup) for an object distributed over 8 sites. This gain is even larger for objects distributed over a larger number of sites. If the level of redundancy is increased further, the gain is substantial. For example, IDA can deliver a 5-fold speedup in communication with the redundancy level set at 50% for an object that is distributed over 32 sites.

For the same amount of redundancy, other protocols (such as replication) yield minuscule speedups compared to IDA. For example, if an object is replicated once ($\frac{1}{2}$ of the communicated data is redundant) and each of the two replica is distributed over 16 sites (for a total of 32-site distribution), then it can be shown that under the exponential delay model, the achievable speedup will be less than 1.1-fold. Under the same conditions, IDA delivers over 5-fold speedups.

5 AIDA-based Bandwidth Allocation

In this section, we highlight the features of AIDA that enable it to deal effectively with deadline and priority issues in time-critical systems.

5.1 Using redundancy to control communication delays

Let the retrieval of an object X be subject to a soft time-constraint that requires X to be fetched within $T^X_{\max}$ units of time. According to equation 4 the expected delay in retrieving X decreases *predictably* as $n - m$ increases. Incorporating the time constraint in equation 4, we can solve for n as follows.

$$\begin{aligned} T^X_{\max} &\geq \tau_e \\ &\geq D_{\min} + \frac{1}{\lambda} \sum_{r=n-m+1}^{n} \frac{1}{r} \\ \lambda(T^X_{\max} - D_{\min}) &\geq \sum_{r=n-m+1}^{n} \frac{1}{r} \end{aligned}$$

[7] These results were obtained under an exponential delay model, but can be easily reproduced for any other model.

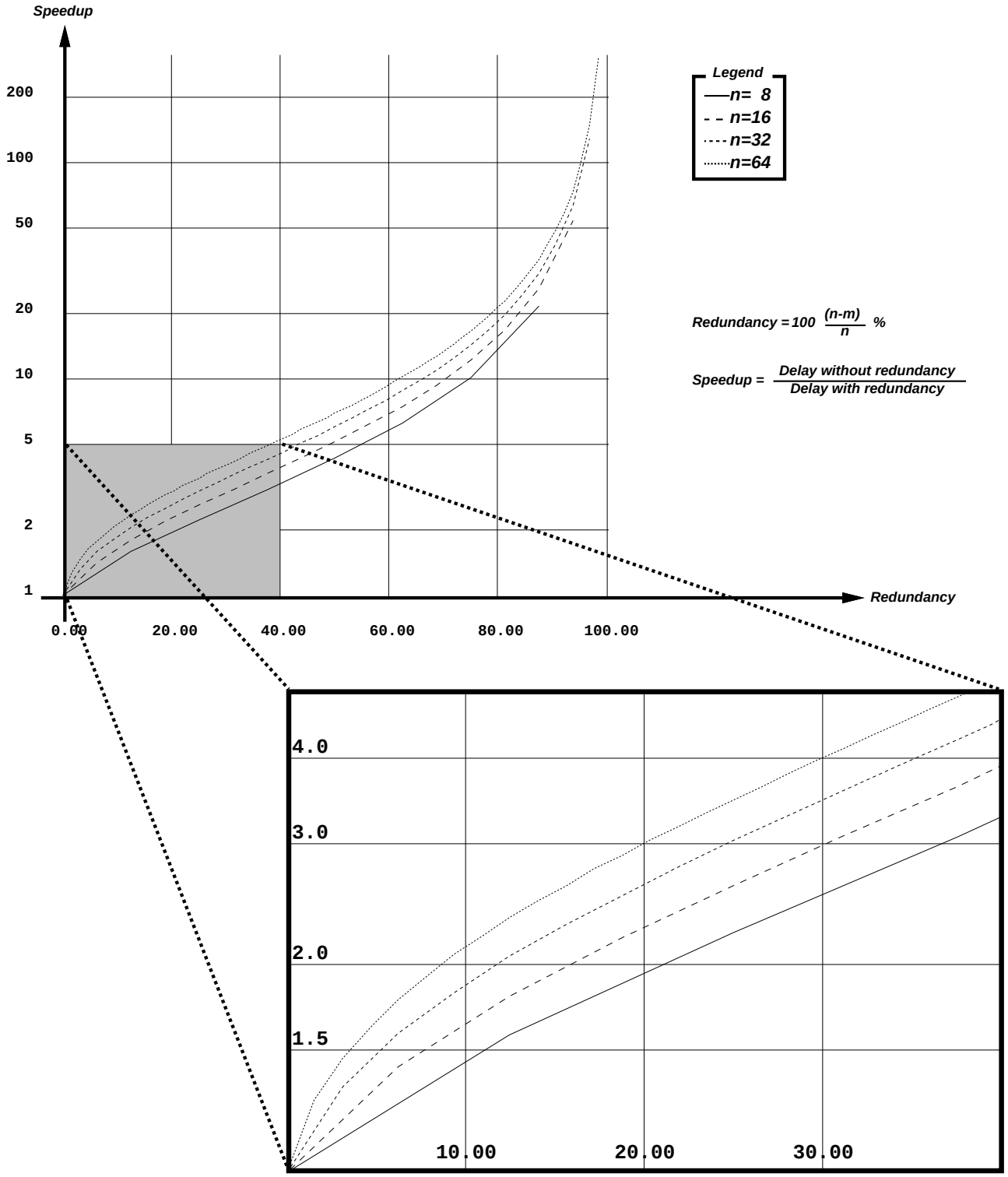

Figure 4: Expected AIDA speedups – Only the random part of the delay is considered.

Using the lower bound $[\ln(n) - \ln(n-m)]$ to approximate the value of $\sum_{r=n-m+1}^{n} \left(\frac{1}{r}\right)$ and solving the resulting inequality for n, we get:

$$n > \frac{m}{1 - e^{-\lambda(T^X_{\max} - D_{\min})}} \tag{5}$$

In order to compute the appropriate value of n using equation 5, it is necessary to evaluate *dynamically* the values of $D_{\min}$ and λ. This can be done using statistical techniques similar to the those described in [10].

5.2 Priority-based rationing of redundant bandwidth

Equation 5 establishes a lower bound on n that guarantees an *expected* communication delay, not an *actual* communication delay. In other words, while it is very possible for the actual communication delay to be less than the desired expected delay (thus satisfying the imposed time constraint), it is very possible as well for the actual communication delay to exceed the desired expected delay (thus resulting in a violation of the imposed time constraint). This *randomness* factor can be accounted for and controlled by using second order moments (*e.g.* , Standard Deviation) to build a *confidence interval* about the actual communication delay. One way of building such a confidence interval is to set the value of n so as to make $T^X_{\max}$, the available slack for completing the communication session, greater than or equal to $\tau_e + \alpha\sigma_e$ (rather than simply τ_e).

$$n > \frac{m}{1 - e^{-\lambda(T^X_{\max} - D_{\min} - \alpha\sigma_e)}} \tag{6}$$

The value of n in the above equation defines a confidence interval that corresponds to a specific probability of meeting the time constraint imposed on the communication session. This probability can be made arbitrarily high by increasing the value of α. This, however, is not without cost. In a distributed real-time system, the total communication bandwidth is *finite*, and increasing the amount of *redundant* information flowing in the system might adversely affect the end-to-end delay characteristics that we were aiming to improve in the first place!

One way of solving the aforementioned problem is to set the value of α in such a way that the total available bandwidth in the system is *rationed* among the different communication sessions in a way that reflects the *priority* assigned to these sessions. In other words, the value of α for a particular task is related to its priority *and* the priority of all the other tasks sharing the available bandwidth in the system.

It is important to notice that using AIDA, the priority of the transaction (how critical it is to the mission of the system) and the urgency of the transaction (how tight its time constraint is) are *both* taken into account when the value of n is determined. This stands in sharp contrast with protocols that deal only with either the priority of the transaction *or* its urgency, making it necessary for applications to express (artificially) one of these attributes using the other.

5.3 Fault-tolerance and Security Characteristics

The usual technique employed to deal with communication failures is to retransmit on errors (or time-outs). For time-critical applications, this detect-then-recover approach might not be feasible due to the time constraints imposed on the system. Instead, masking techniques are employed. In particular, error-correcting codes are used to tolerate communication failures, whereas replication and/or n-modular redundancy (NMR) techniques are used to protect against site failures [20]. The main drawback of these techniques is their excessive use of redundancy, which might adversely affect performance. For example, to mask one site failure an approach relying on replication will require that a particular object be retrieved from two different sites, thus doubling the network traffic. The blowup is even larger when error-correction for a relatively small number of communication-induced errors is taken into account.

The AIDA-based protocol we are proposing in this paper is a failure-masking protocol that is provably optimal in its use of redundancy. The main reason for AIDA's superiority is that it does not distinguish between communication failures and site failures, thus making the best use of allotted redundancy in the system. To tolerate up to r simultaneous failures, AIDA requires that the total number of sites from which the dispersed object X will be requested exceeds the minimum number of data pieces needed to reconstruct X by r. Thus, a total of $n = m + r$ sites is needed for every m pieces of data, a redundancy of $100(n - m)/m$ percent. For example, if an object X is to be dispersed over $n = 12$ sites and coverage for up to 3 failures is required, then using AIDA, the total redundancy would be 25% (a blowup of 33%). To provide the same coverage using replication, the total redundancy would soar to 75% (a blowup of 300%).

A common technique to insure communication security is to store and communicate information using some form of encryption, where only authorized users are enabled to decrypt the information through the use of appropriate *secret keys* [22]. The proven difficulty of decrypting the information without knowing the secret key guarantees a high level of *security*. The main disadvantage of this technique is that the information (although encrypted) is available in one site – whether stored in or communicated through that site – for long periods of time. This might make it possible for adversaries to break the secret key of the encryption.

The AIDA-based protocol we are proposing in this paper guarantees the security of the communicated information by making it unavailable as a whole in any one particular site. As a matter of fact, it is hard to get any clue about the original information unless at least m pieces from the dispersed file are collected. This makes the task of the adversaries more difficult, since they have to control m of the sites and not only one. Even if this happens, it is provably very difficult to reconstruct the original file unless the secret key is known.

6 Conclusion

AIDA is a novel bandwidth allocation strategy suitable for distributed fault-tolerant time-critical systems. In AIDA redundancy is used to *tolerate* failures, to *increase* the likelihood of meeting tight time-constraints, and to *ration* (based on task priorities) the limited bandwidth in the system. In this paper we have presented AIDA's potentials and established its superiority with respect to existing protocols. The implementation of an AIDA-based network file-server that would act as an interface between the application programs and the communication network is our next goal.

Several variants of the basic ideas presented in this paper are under investigation. For example, we are evaluating a number of possible mechanisms to be used for the selection of the n out of N sites to be consulted for an object retrieval. While the correctness and efficacy of AIDA are not dependent on such mechanisms, its performance might benefit greatly. Similar performance gains can be achieved by classifying communication requests as was done in [15, 16]. Such a treatment is likely to reduce the uncertainty associated with communication delays, thus providing for a more efficient allocation of bandwidth.

Another area of particular interest is the susceptibility of AIDA to sudden changes in the communication delay characteristics, whether as a result of an influx of sporadic communication requests, or as a result of a sudden decrease in bandwidth due to failures. Simulations that would relate such susceptibilities to system design parameters (for example frequency and sample size to be used for estimating the *actual* delay characteristics), are underway.

In this paper we focussed on information retrieval. Issues pertaining to information *update* were not tackled. These issues are particularly important in distributed time-critical systems to ensure data consistency and recency. In particular, it is of utmost importance to investigate the interaction between AIDA and other consistency-preserving protocols such as distributed shared memory protocols [23], caching protocols [1], and non-coherent memory protocols [13].

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