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Signal Propagation Delay as a Barrier to Control Applications in WAN.

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Abstract:

With the advent in WAN of delay sensitive technical applications, such as remote control, signal propagation delay becomes a major problem. The extent of the problem is analysed by lower bounding the delay in relation to different transmission media. Requirements for reliability and bandwidth are considered. The consequences of this bounding for communication network planning and provisioning are discussed in relation to mitigating the effects of signal propagation delay as a barrier to the penetration of control applications into WAN.

Keywords: Networks, Delay, Resource Management, Network Infrastructure, WAN.

1. Background

In the past few years QoS demanding applications have been entering the MAN and WAN area, and this development is expected to continue with the increasing convergence of communication services [1] and with increasing demands on the structural and physical properties of the underlying infrastructure [7]. Most widespread today are the streaming media applications but, increasingly, a number of control applications are following suit. The latter presents both an opportunity for reducing cost through centralising control of multiple plants, such as power stations, and development of a new level of distributed systems. This poses new challenges to communications systems. Where streaming media are primarily sensitive to bandwidth limitations and delay jitter, control applications are characterised by sensitivity to total delay in the control loop. Control applications have the

purpose of regulating a system to ensure that it is functioning within some parameters, such as maintaining a temperature or output level. To do so, it is necessary to sample the current value of the system with some frequency, and based on this sample value to calculate corrections to the system. For such a control loop to be stable the correction must be applied to the system before the next sampling of the system. Preparing new networks for optimum support for such economically significant applications presents a major consideration for resource management and network planning and provisioning.

Substantial research has been made in the area of delay in networks. The focus of this research has been on queuing and methods for upper bounding the delay, primarily in relation to single nodes. Delay in end to end transmission consists of several components, namely delay due to signal conversion, queuing and signal propagation speed in the transmission media. Of these factors the delay due to signal propagation is the least tractable. This paper treats end to end transmission delay as a lower bound problem in order to answer the question of how global can control applications become, and under what conditions. The approach is to evaluate possible transmission technologies based on propagation speed, reliability and bandwidth. It is then discussed to what extent it is plausible that this lower bound may be achieved. Guidelines for experiments are given. Finally a discussion of the possible extent of control applications into WAN is given.

2. Propagation delay fundamentals

With the exception of certain exotic phenomena in quantum mechanics known as the non-local

interactions all cause and effect is limited by signal propagation speed. This speed can not exceed the speed of light in vacuum, 299,792 km/s. Since the non-local interactions can not be exploited for communications purposes, this speed limit becomes an absolute limit on communication. In any media denser than vacuum the propagation speed of electromagnetic waves decreases; this is expressed by the refractory index of the media. For wireless transmission in the earth atmosphere this speed is approaching the speed of light, whereas in wired transmission the speed drops significantly. For instance, common values for refractory indexes in optical fibers are around 1.49-1.50 giving an approximate signal propagation speed of 200,000 km/s. On a global scale where distances range up to 20,000 km the consequences are significant.

3. Modelling parameters

Modelling the problem implies taking into account some other transmission factors that are indispensable in relation to control applications, namely QoS. Here reliability of the connection is foremost, as the system is "out of control" if for any reason sample data or control data is lost. Normally there is a limited tolerance to the occasional loss of a single update cycle, but much more than this can cause the system to halt. Many applications of control involve systems where an emergency halt or loss of control will be highly costly or outright dangerous, such as power production that may cause large-scale power failures, as has been observed recently in several countries. The cause of the original failures may vary but the large-scale failures resulted from lack of control over the power grid and production facilities in the face of power plants dropping off the net.

Bandwidth is also a factor as with wireless transmissions all users share this common and limited resource. In common this problem is mitigated through use of a cell structure where wavelengths are reused and where long haul transmission is handled in a wired transport network. In this context such a scheme can not be reconciled with the advantages of higher propagation speed in wireless transmission, as speed for inter-cell communication drops to that of the wired medium. Thus, even for low bandwidth demanding applications long haul transmissions place significant demands on a shared resource.

4. Wireless transmission

Wireless transmission presents the highest signal propagation speed. The density of the air only lowers

the propagation speed of electromagnetic waves by a few kilometres per second even at sea level. Transmission characteristics, though, vary greatly with wavelength: In the lower radio frequencies long range (beyond the horizon) transmission is based on the waves rebounding off higher layers of the atmosphere. This enables global transmissions but also introduces a factor of low reliability, as the reflectivity of the higher atmospheric layers change with the magnetic envelope of the earth and is highly susceptible to changes in solar activity [5]. Larger solar eruptions greatly alter the state of these layers, occasionally causing signal reception to be interrupted in areas. At higher frequencies relay stations are needed to follow the earth's curvature, either ground based or satellites. In the microwave and optical wavelengths interference from particles such as water vapour hinder reliable transmission with the exception of some "windows" in the microwave bands, that are today employed for satellite transmissions. At higher wavelengths the ozone layer and Rayleigh scattering also limit transmission capabilities. Bandwidth limitations for transmission windows apply only within the atmosphere; at low earth orbit (LEO) heights the optical spectrum can be employed unhindered.

Use of ground based relay stations can not provide a real alternative as such systems are confined by the limited bandwidth available within the earth's atmosphere and inability to reuse frequencies in cell structures. As most of the available frequencies are also already allocated, mostly for different wireless access technologies ranging from television over airplane communication to mobile phones [3], establishment of a wireless transport net is unrealistic at best.

Satellite systems offer a better bandwidth utilisation as only the up- and down-link must depend on the limited transmission windows. Medium earth orbit (MEO) systems and higher orbits suffer from the increased distances and can not compete with wired ground systems. LEO satellite systems offer the better choice. In relation to control applications reliability of such systems are at present insufficient with availability around 99.5-99.9 [4].

5. Wired communication systems

Wired communications systems are today becoming synonymous with optical communications systems. Although other media are still dominating in the access link, the transport nets have made the transition. Since propagation speeds of other wired transmission systems are also comparable to optical fiber or significantly lower [6] only optical fiber networks are considered. The refractory index and

	Ground based wireless	LEO satellites	Higher Orbit Satellites	Wired networks
Advantages	High propagation speed; shortest path.	High propagation speed; global connectivity; few hops.	Fewest hops; global connectivity.	High reliability; high bandwidth; low bit error rate; high security.
Disadvantages	Limited shared bandwidth; conflict with cellular principle for long range transmission; frequencies allocated for other applications.	Only useful for long range distances due to uplink distance; low availability; limited bandwidth in uplink.	Very long uplink distances; low availability; limited bandwidth in uplink; larger “footprint” in downlink.	Lower propagation speed; links must conform to geological limitations; costly to modify structure.
Usability	Within local area conforming to cellular principle.	Long distance with low bandwidth requirements.	-	All distances where high reliability and bandwidth are needed.

Figure 1. Transmission properties overview.

thus propagation speed of light in the fiber are the fundamental properties allowing optical waveguides to function. The figure of 1.49-1.50 is almost universally valid giving a propagation speed of 200,000 km/s. Fiber-optical networks can provide the necessary reliability for control applications through two or more independent paths, guarding against cable breach. Bandwidth limitations are relatively speaking no issue in fiber optical networks.

6. Achieving the lower bound

For circuit delay to achieve the lower bound given by the signal propagation speed, other delay factors must be overcome. These are notably delay imposed by active components and delay from a circuitous signal path. In optical fiber networks active components delay stems from routing/switching and signal conversion/regeneration. Much research is going into limiting the delay of active components. This takes two directions; reducing and bounding delay within an active component, such as queuing delay, and reducing the number of active components in end to end transmission [2]. As these factors become less significant in the end to end delay, this delay converges on the propagation speed limit. Drastically reducing the number of routing and switching nodes in a path does pose a connectivity problem, as to retain connectivity the number of lines connected to these nodes rises inversely. Achieving the lower bound in this respect corresponding to a

fully connected network is practically and economically unfeasible.

LEO satellite systems are, so far, dimensioned with less than 100 satellites. This implies that each satellite covers a relatively large part of the earth and, followingly, that the satellites are less than ideally placed for up and downlink. As such LEO satellites are fast moving there will always be periods of time for every location when no satellite is close overhead and up- and downlink delay thus increases due to longer distances. LEO satellite systems are thus only superior to wired systems where the total distance is large enough to allow the higher propagation speed to compensate for delay due to unfavourable satellite positions. A similar problem is posed for wired systems where cable layout rarely trace a straight path between the two connected points giving a longer overall path than the geographical distance between the end points. Thus, if delay in a wired communications network is to converge on the minimum possible the structural layout is paramount in minimizing delay.

7. Consequences

Considering that the ideal lower limit on delay for wired systems between such significant areas as India and the US is close to 0.2 second it is immediately clear that many time-sensitive control applications will never reach a global scope. Modelling this problem exactly is unfeasible, mainly due to the geological layout of the earth and an even more uneven distribution of population and industry. The

problem is therefore modelled abstractly as delay versus number of potential connected points derived from surface area of a sphere, disregarding that the earth is a spheroid, not a sphere, see Figure 2.

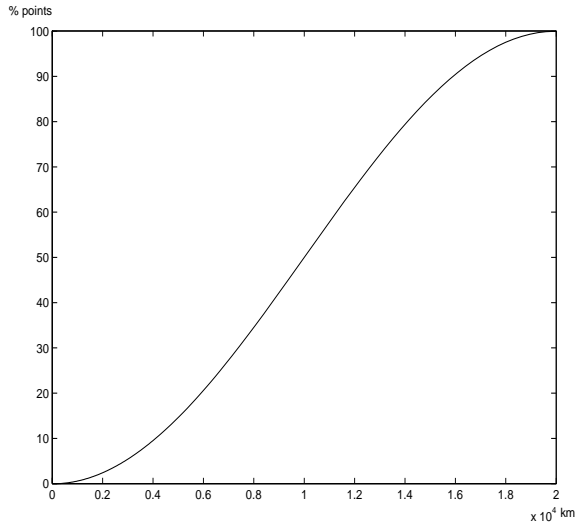


Figure 2. Cumulative connection points as function of distance.

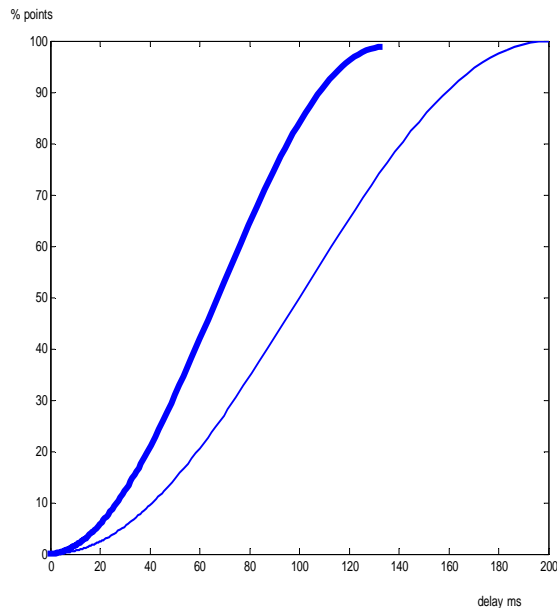


Figure 3. Cumulative connection points as function of propagation delay in round trip communication. Heavy line represents wireless and LEO, thin line fiber optical networks.

Given the results in Figure 3 it must be expected that time sensitive control applications will continue to evidence strongly localized traffic patterns. Only applications with sampling rates above .5 second can be expected to achieve truly global scale. For a control application with sample rate of .02 second propagation delay alone limits its extent to less than 10% of all possible connections. This lower bound represent the best possible situation and can only be approached through a coordinated planning and provisioning scheme encompassing network layers 3 and lower.

8. Experiments

Substantial experimental work must be undertaken to determine exactly how close end to end delay can come to this lower limit. This problem must be considered in two ways; one way in relation to minimizing global delay within a path of given length, that is delay from active equipment, and the other way in relation to placement of paths in the physical world, converging path lengths on the ideal great circle path on a sphere. For experimental work on reducing active components delay the problem is not only one of reducing delay, but also of retaining full connectivity in the networks. Experimentation must therefore be carried out with the constraint, that the number of active points can not be reduced further than the minimum needed to provide connectivity to all points; thus, it must be possible to map out a spanning tree for the network with a maximum height equal to the number of active points in the path assuming only practically feasible routing and switching schemes. This is challenging if for no other reason than it requires full control over long distance transmission paths. Some extrapolation from short paths is of cause possible. A set of requirements for such a path is suggested here.

An end to end transmission path must be controlled in order to avoid interference from other traffic. All active equipment must be known and optimized for fast throughput. The path should contain least possible number of hops. The physical length and refractionary index of each link must be known to distinguish propagation delay from active components delay.

Experimentation on placement of physical paths is of a different nature, as this deals in the main with geological and economic considerations of price for placement, life expectancy of the cabling and repayment of investment.

9. Discussions

The lower bound on delay presented here is based on absolute physical properties and as such must be assumed to remain valid indefinitely. For control applications and other delay sensitive applications this implies that WAN will only be able to provide the necessary infrastructure to a limited extent. Conversely, as the preconditions for such applications are suboptimal, it must be considered paramount in resource management and network infrastructure planning to optimize structural properties and choices of transmission technologies for these applications. Particular attention must be given to placement of wired links to avoid circuitous paths. Significant economic gains can be realised from improved coordination and control of industries and resources; the extent of such gains will be determined by whether the WAN infrastructure in the future remains a connectivity-focused, least cost project or becomes focused on providing the necessary structural qualities. Much further research is needed in this area to lay down clear guidelines for network resource management.

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