A Congestion Control Algorithm for Signalling Networks Based on a State Machine Controlled by Network Delays

Lars Angelin and Åke Arvidsson

Dept. of Telecommunications and Mathematics,
University of Karlskrona/Ronneby,
S-371 79 Karlskrona, Sweden

Abstract

Congestion control in Signaling System number 7 faces new challenges as mobile communication systems and Intelligent Networks grow rapidly. New services change traffic patterns, add to signalling network load, and raise demands on shorter service completion times. To handle new demands, the congestion control mechanisms must foresee an overload situation, and respond to it so that the network can maintain high throughput. With the introduction of a state machine and a memory function for each signaling link it is possible to predict the completion time of a service session and to detect an emerging congestion. If the predicted completion time of a service session is too long, the session is annihilated. This is the foundation of a congestion control mechanism that reacts fast on information supplied by the network. The congestion control mechanism enables the network to maintain a high throughput during overload.

1. Introduction

The evolution of IN and mobile communications requires services of high complexity, and alters signaling traffic patterns, as compared to ordinary PSTN services. A complex service, such as the hand over procedure in mobile communications, needs more signals before completion, has higher demands on real time efficiency, and involves more nodes, than any service in the PSTN [1,2].

Moreover, as new services are introduced, the number of simultaneous sessions to be handled by the signaling network increases, thereby increasing network load. Present congestion control mechanisms in Signaling System #7 (SS7) are primarily designed to cope with traditional call set-up and call release in the PSTN. All in all, this necessitates a new approach to efficient network solutions for signaling network congestion control.

Sessions of a service with high real time demands which are subject to unacceptable delays may be obsolete, or prematurely terminated by the customer; in either way, they are just a burden to the signaling network. It would ease the load of the network and improve overall performance if such delayed sessions could be aborted as quickly as possible. The annihilation of sessions for which the first two signals consume more time than an allowed fraction of the allowed service completion time, has proven to be a well functioning congestion control mechanism (CCM) [3]. The introduction of a state machine and a memory function for each signaling link makes it possible, even before any signal of the session has left the originating node, to predict the completion time of a service session with good accuracy and to detect an emerging congestion [4].

2. Congestion control in signalling networks

2.1 Congestion control functions in signalling networks

An SS7 network is a packet switched network with the sole mission to support telephone networks. The signalling network consists of a number of Signalling Points (nodes) and Signalling Transfer Points (transit nodes) connected via Signalling Links (links) in a mesh structure [5, 6]. The information communicated between the nodes to conclude a signalling service session is transported in signals guided by a routing algorithm. In case of link outage, or congestion, the routing algorithm must redirect the signals through the network in such a fashion that healthy parts of the network are not overloaded, i.e. the robustness of the routing algorithm is not negotiable [7]. This suggests that the properties of the routing algorithm are inseparable from flow and congestion control in setting the boundaries for signalling network performance. A large number of routing algorithms have been thoroughly investigated, and their properties are well known, all ranging from fixed routing to very sophisticated adaptive routing algorithms [6].

A signalling network is engineered in such a fashion that normal load represents about 25-35% of maximum load, suggesting congestion to be very unlikely at normal working conditions. Congestion is more likely to arise from traffic redirections at network component failure, or by an extremely high call intensity to one specific node [8]. The traditional role of a CCM in SS7 is to resolve an immediate overload situation in a link or a node by throttling the traffic with destination to the congested area without any regards to the impact on the surrounding network.

A good CCM must be able to resolve the overload situation in such a manner that the entire network benefits. Furthermore, it must be able to foresee an emerging congestion, and to take adequate prophylactic steps in order to normalize the situation [5].

2.2 Network delays as a foundation to a CCM

An increase in offered signaling network load will increase the signaling session completion time, and further increase in offered load will eventually cause congestion with session completion times approaching infinity (fig.1). Two conclusions may be derived instantaneously:

i) The signaling session completion time contains information about network load, and thus indirectly information concerning the congestion state in the network. This information may be used both as a parameter in a routing algorithm or in a CCM.

ii) Signaling sessions with real time demands will not easily be able to meet these demands during high network load.

The carried load, i.e. the number of sessions completed within their allowed service completion time divided by the number of a generated sessions at an offered network load of 1.0, increases in proportion to the increase in offered load (fig. 2). When the offered load increases beyond a certain value, the load threshold, the carried load reaches its maximum and then falls dramatically. The load threshold is determined by the real time demands of the signaling sessions. A reduction of the real time demands moves the load threshold to a higher offered network load, and vice versa. The effect may be interpreted as a virtual congestion, more severely experienced by services with high real time demands, long before an actual congestion arises. This implies that congestion control is a necessity at all conceivable network loads when real time demands are present.

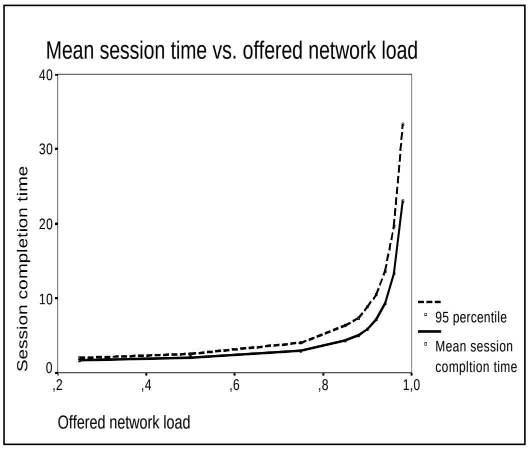

Figure 1. The relationship between offered network load and session completion times.

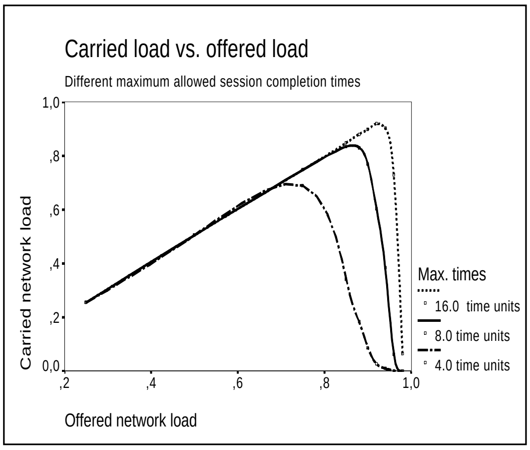

Figure 2. The relationship between offered network and carried network load. The 95% confidence intervals are within +/- 0.05 of the curves.

A signalling service session that exceeds its allowed completion time displeases the customer and deteriorates network performance by occupying buffer space and processor capacity without contributing to the carried network load. In a normally engineered network, signals of such sessions have with high probability encountered a congested part of the network. Signalling sessions encountering congestion fuel the congestion, and consume much time in penetrating the congested part of the network. The annihilation of such sessions would serve the dual purpose of reducing the load of the congested part as well as freeing communication facilities, and thus enhancing the possibility for other sessions to meet their real time demands. If knowledge of the duration of sessions could be obtained prior to their completion, it would be possible to annihilate sessions with too long completion time or to prevent them from getting started. This is the foundation of a benign CCM, one that detects a congestion at an early state and acts to reduce the flow in the congested direction.

3. A CCM state machine

3.1 An estimate of the network load

The signal completion time contains information about the network load. This information may be used in two ways, one regarding the link between the originating and the destination nodes and one regarding the overall load situation in the network.

The completion time of the most recent signal on a link is a good estimate of the completion time for the next signal to traverse that link if not too long time has elapsed between the two events. To achieve a correlation above 0.8 between the two, “too long” means more than one average signal completion time at an offered network load of 0.25, and about 7 at an offered network load of 0.95. This in spite of the average signal completion time being roughly 10 times greater at the 0.95 offered network load as compared to the 0.25 load.

An estimate of the overall network load from an originating node *i*’s perspective in a network with N possible destination nodes, d_j where $j = 1, 2,.. .,N$ and $j \neq i$, and event n is to take place, is given by

$$L_n = \frac{\sum_{j=1}^{N} P(d_j, n-1)}{\sum_{j=1}^{N} M(d_j)}$$

where

$P(d_j, n-1)$ = the present prediction of the signal completion time between the originating node *i* and the destination node d_j, calculated with L_{n-1}

and

$M(d_j)$ = the smallest measured signal completion time between the originating node *i* and the destination node d_j.

3.2 The state machine

The two ways of using the completion time information may be molded together onto a state machine to produce a prediction of the signaling session completion time (fig. 3). The prediction of a service session completion time is updated when a signal is about to leave the originating node, i.e. even before the first signal of the session has entered any link.

There is one state machine per origination-destination pair, and it consists of three states, and of three transitions. A brief explanation of the states and transitions is presented below.

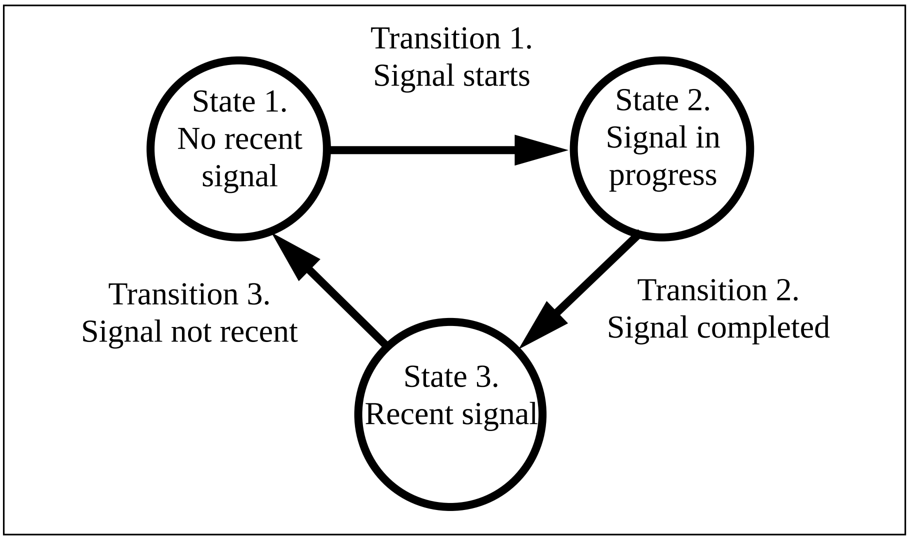

Figure 3. The state machine with its states and transitions.

State 1. The link has been idle for such a long time that the most recent signal completion time is no longer valid as a prediction for the completion time of the next signal. We then set $P(d_j,n) = a\ M(d_j)L_n$. The constant scaling factor a determines the state machine's impact on system stability in such a fashion that $a > 1$ causes instability, while $a < 1$ keeps the system stabile. To obtain a stabile but reasonably fast system a has been set to 0.97.

Transition 1. A signal is sent from node i to node d_j.

State 2. The signal causing Transition 1 has not yet returned to node i. We set $P(d_j,n) = t+b\ M(d_j)L_n$, where b is set to 1.0 and t is the time so far consumed by the signal.

Transition 2. The signal in State 2 has returned to node i.

State 3. There exists a recent signal completion time, $R(d_j)$, that can be used as a prediction for the next signal. Here we set $P(d_j,n) = c\ R(d_j)$ and here is also c set to 1.0.

Transition 3. Too long time has elapsed since the last signaling event. This happens when *Elapsed time* $= d\ R(d_j)L_n$, where d is set to 0.5 in order to speed up the state machine, especially when the offered network load decreases rapidly.

The values of the scaling factors a,b,c and d are primarily chosen to make the model simple and not to optimize the performance of the state machine.

3.3 Prediction of session completion time and annihilation criteria

A service session in our model has one originating node, *i*, and *k* randomly selected destination nodes, d_j where *j*=1, 2,.. .,*k* and $j \neq i$. Signal *j* is divided into two parts. The first part traverses the network from the node *i* to node d_j and then the second part of signal *j* completes the round trip back to node *i*. A service session then comprises *k* signals. The prediction of the completion time of a signaling session originating in node *i* and comprising *k* signals of which *l* signals are already completed is calculated as

$$D(k, l) = \sum_{j = l+1}^{k} P(d_j, n) + \sum_{m=1}^{l} t_m$$

where t_m is the actual time consumed for signal *m*. *D(k,0)* is the initial prediction for a session of *k* signals which is made before the first signal of the session has left the originating node.

A simple CCM is to annihilate signaling sessions for which the prediction *D(k,0)* is greater than a set time limit depending on the maximum allowed session completion time. The time limit may be derived from time critical services in the network, such as the hand over procedure in cellular networks, or simply be set in such a fashion that it protects the network from congestion.
The annihilation procedure in this study is as follows:

i) Determine the shortest possible completion time for session *s*, originating in node *i* and comprising *k* signals

$$min(s) = \sum_{j=1}^{k} min(d_j)$$

ii) If *D(k,0) > A min(s),* session *s* is annihilated.

and the real time demands of a session are, in this study, treated in the following manner:

If *D(0,k) > B min(s),* session *s* has not met its real time demands and is considered not successfully completed.

To make the annihilation criteria and the session real time demands work together it is obvious that $A \leq B$. The constants *A* and *B* are throughout this paper set to 6.0 and 8.0 respectively, making the maximum allowed session completion time 8.0 time units (t.u.). The constants are not chosen in order to optimize performance, but to avoid the curves in the diagrams from interfering to much at an offered network load of 1.0 and to clearly visualize the performance of the proposed CCM.

Since several services are supported in a real signaling network, each with its unique service characteristic, one single time limit is not satisfactory as an annihilation criteria for service sessions. The annihilation criteria may by added as a service characteristic for each specific service, this is possible without corrupting either the proposed CCM or the service [9]. In a wider perspective it is not only the network itself that must benefit from a CCM. The network operators' objective is to optimize the financial profit from the signaling network. The CCM can be one tool in achieving this task, using the CCM to annihilate the least profitable sessions first [10].

An investigation reveals a correlation in the order of 0.9 between *D(k,0)* and the actual completion time of the session through a wide range of offered network loads (fig. 4). This in spite of an offered load pulse being present per analyzed offered network load point, as described in fig. 7. A more detailed study shows that the proposed CCM underestimates the session completion time at a positive transient and overestimates it at a negative transient.

The small dip of the correlation around an offered load of 0.5 may be explained by frequent transitions between the states in the state machine. At low offered load State 1 is predominant and at high load State 3 is rarely left.

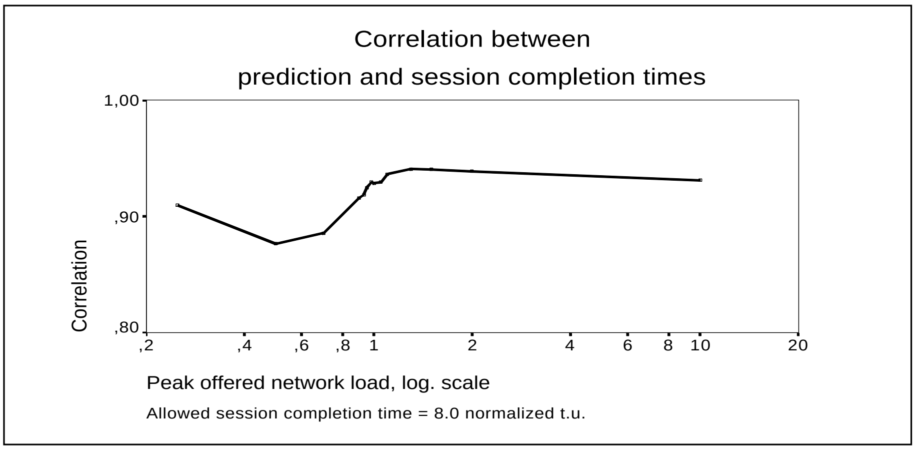

Figure 4. Correlation between the completion time of a session and the predicted completion time of the session. Note the logarithmic scale on the x-axis.

In other words, it is possible to make a good prediction of the completion time of a session, and to predict how it will meet its real time demands. A good prediction of the completion time of sessions also makes it possible to detect an actual or an emerging congestion with good accuracy since session completion time is closely related to network induced signal delays and thereby related to network load.

4. Numerical results

4.1 The signalling network model

The nodes in the network model comprise both Signalling Point and Signalling Transfer Point functions in the sense that all nodes may initiate or terminate service sessions and they can all transfer incoming signals towards the final destinations. Each node is divided into two parts: the lower layers and the upper layers, representing the OSI layers 1-3 and 4-7 respectively. In the lower layers there is also a signal discrimination function for routing an incoming signal to either the upper layers of the node or to an outgoing link for further transport in the network (fig. 5)

Each composite layer is represented by a queue with an FCFS queuing strategy and with the service time being the sum of a constant time and a time derived from a negative exponential distribution. The mean service time of the server in the lower layers is fixed, and set to 1.0. The mean service time for the upper layers is variable to model the complexity of the processing performed by the upper layers, and the two service times 1.0 and 10.0 have been studied. In the sequel, the two cases are referred to as short upper layer response time and long upper layer response time respectively.

The network, on which this analysis is performed, is a symmetrical 20 node mesh network (fig. 6) with four bidirectional links per node. Fixed routing is employed in such a manner that all signals traversing the network from node A to node B use the same route, while signals from node B to A may use another route. Signals may pass up to three nodes in order to reach their destination, and thereby interact with a total of five nodes. The transmission delays are incorporated in the lower layers service times.

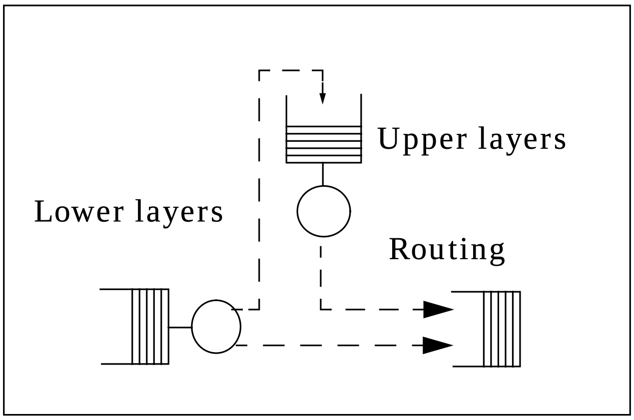

Figure 5. Queueing model of node interior.

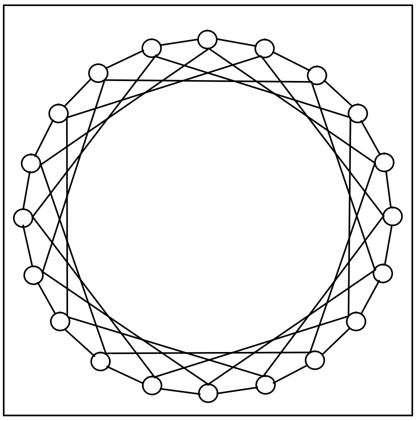

Figure 6. Network based on nodes and signalling links.

The offered load is uniformly distributed between the originating nodes, and it is derived from a negative exponential distribution.

In this investigation is the number of signals, k, per service session derived from a uniform distribution and is in the range of $1< k < 19$. In PSTN is the number of signals per service session less than 10 for all services, while in GSM, it may even exceed 40.

4.2 The metric

We use the carried load, i.e. the number of sessions completed within their allowed service completion time divided by the number of a generated sessions at an offered network load of 1.0, as a metric. The metric discloses the network’s ability to handle the present offered network load under the constraint of service related real time demands. It also reveals the possibility for a session to fulfill its mission as requested by a customer, and is thereby closely related to that part of customer satisfaction that is derived from network performance.

The carried load cannot reach 1.0 if signaling session real time demands are present. See fig. 2 for maximum carried load at a given maximum allowed session completion time in an unadulterated network. E.g. the maximum carried load is 0.83 and the offered load threshold is 0.86 for an allowed session completion time of 8.0 t.u.

4.3 Static behavior

The impact of the proposed CCM is negligible at normal offered network load and increases dramatically with offered network load [3, 4]. In other words, it does not interfere with the network under normal working conditions, i.e. an offered network load below 0.5, but steps into action when congestion arises. Simulations reveal significant improvements of throughput, compared to an unadulterated network, at offered network loads above 0.5.

Varying the mean upper layer response time, the time scales alters, but the general behavior of the algorithm remains. This suggests the proposed CCM to be robust in terms of the processing complexity required in the upper layers.

4.4 Transient behavior

The network is subject to a pulse in offered load to facilitate a study of its behavior during transients (fig. 7). The magnitude of the pulse ranges from 0.5 to 10.0. Before initiating the pulse, the network is kept at low offered load (0.25) until a steady state is reached. The duration of the pulse is long enough to let the network enter a new steady state. The offered load of 0.25 is resumed after the offered load pulse. The proposed CCM follows the pulse well and was able to maintain and even, at offered network load in excess of the load threshold, increase the carried load for a given maximum allowed session completion time (fig. 7 and 8).

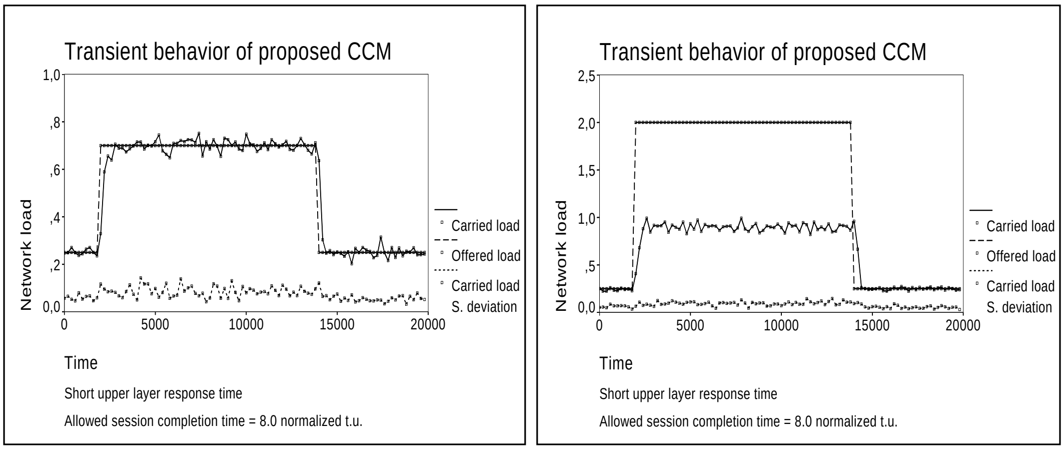

Fig. 7. The transient behavior of the proposed CCM at the single step loads of 0.7 and 2.0 respectively. The dashed line represents the offered network load and the solid line represents the carried load while utilizing the proposed CCM. Time is not equivalent to time units (t.u.).

The maximum allowed session completion time is 8.0 t.u. in all diagrams below. The diagram on the left in fig. 7 shows the network under an offered load pulse of magnitude 0.7 which is lower than the load threshold value. The CCM produces a carried load in accordance with the straight slope in fig. 2. On the right, the magnitude of the offered load pulse is 2.0 which is well above any conceivable load threshold value for an unadulterated network. Still, the CCM produces a carried load higher than obtainable from an unadulterated network. The annihilation of sessions with a predicted time exceeding *A min(s)* gives an "extra space" in the network for sessions with a predicted time below *A* *min(s)*, and that extra space increases the probability for the surviving sessions to meet their real time demands, thus the increase of carried load.

The slope of the carried load at the transient in fig. 7 is partly due to the time it takes to build up the new load in the network, and partly to the reaction time of the proposed CCM. Nevertheless, the time span of the slope is no longer than a few session completion times. The conclusion must be that the proposed CCM is able to protect the network at rapidly emerging congestions, while maintaining a high carried load.

This investigation includes long upper layer response times (fig. 5) and the results are almost identical to the results achieved with short upper layer response times.

4.5 Comparison to existing SS7 CCM

Congestion control already exists in SS7 and it has some impact on the signalling network. The proposed CCM challenges the existing SS7 CCM and a comparison between the two is inevitable. The SS7 CCM is based on traffic information sent between nodes in Link Status Signalling Units, which are internal SS7 administrative signals [6, 8]. The information can originate from the signalling link layer levels or the User Part levels and concerns the state of the input buffers at these levels. The receivers of the information have then to take proper action, i.e. either to cease or throttle the signalling towards the congested node. Affected signals and sessions are discarded or terminated as quickly as possible. When the buffer levels pass below a certain value, Link Status Signalling Units are sent to the concerned nodes and signaling is resumed. A model of the SS7 CCM functions above mentioned is incorporated into the studied model. After finding suitable buffer levels for the SS7 CCM model it is possible to conduct a comparison between the two CCMs. The result is presented in fig. 8 and the carried load for a network without CCM is also shown in the diagram.

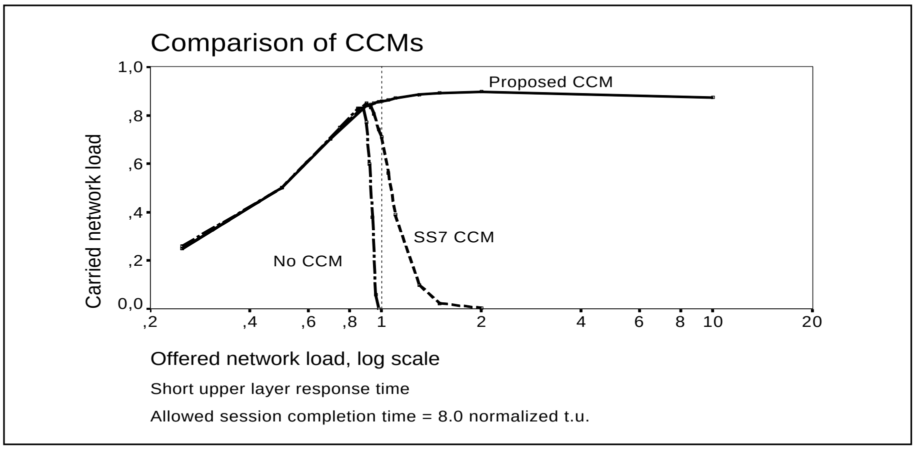

Fig. 8. Carried load vs. offered network load. The proposed CCM (solid line) and our interpretation of existing congestion control in SS7 (dashed line) compared to network behavior without congestion control (dash-dotted line). The 95% confidence intervals are within +/- 0.05 of the CCM lines. Note the logarithmic scale on the x-axis.

The implemented SS7 CCM is deliberately given a benevolent interpretation, and it does not entirely comply with CCITT / ITU/T standards. One difference is that the Link Status Signalling

Units traverse the network instantaneously in virtual signaling links, i.e. information concerning congestion will, without delay, reach every concerned node. Thus, terminating the involved sessions immediately without adding to the congestion.

The proposed CCM performs very well even at extremely high loads and in such a fashion that the overload is hardly noticeable for the network. Our interpretation of the SS7 CCM performs reasonably well only in the low overload region.

4.6 Interarrival times

The interarrival times for the generated sessions follow a negative exponential distribution, and our analysis shows that the distribution of the interarrival times of the accepted sessions is close to the negative exponential distribution, but with a slight increase in the probability for the longer interarrival times. This indicates that the proposed CCM is both stabile as a control algorithm and fair in its session acceptance policy, rather than exhibiting an oscillating behavior in both instances.

5. Conclusion

The work demonstrates the possibility of using information derived from the completion time of the signals in a signaling network to gain knowledge of network performance, and thereby detect congestion. This information may also be used to design a signalling network CCM that operates independently of applications, and independently of nodes.

A simple CCM that predicts the session completion time from the most reliable signalling events of a node, and annihilates the session if the predicted completion time is found to be too long, improve network performance at congestion significantly. This applies to a signaling network both during steady state and transients loads. The proposed CCM has proven to handle very high overloads without any loss in carried load. It even increases the carried load under favorable circumstances.

The proposed CCM steps into action when a congestion is detected and reduces the load in the proper directions while being fair to all service classes [10], to all call attempts, and to services traversing any number of nodes.

6. Future work

The studied CCM can be refined in a number of ways. One way is to choose the constants *a,b,c,* and *d* with more care. Another way is to consider $L_n(i)$ for each outgoing signalling link and not as present, per node and calculated on information from all outgoing links in that node.

The proposed CCM cannot be expected to reveal all possible flaws or benefits unless studied under more realistic circumstances. The assumptions in this paper of a symmetrical mesh network with uniform service call intensity distribution over the nodes, constitute only a small fraction of possible working conditions for a signalling network. A thorough investigation of the CCM performance must include unsymmetrical signalling mesh networks exposed to non-uniform service request intensities. Focused overloads must also be investigated since most congestions are located toa small part of a node or a network. Furthermore, the stability of the proposed CCM must be studied more thoroughly.

Congestion control is not separable from routing. The proposed CCM must also be able to work in conjunction with routing algorithms.This aspect is not investigated in this paper.

7. References

[1] B.A.J. Banh and G. Anido, “Signalling Network Design Aspects For Mobile Services”, Proceedings of the Australian Telecommunication Networks & Applications Conference, pp. 695-700, Melbourne, 1994.

[2] J. Zepf and G.Rufa, “Congestion and Flow Control in Signaling System No. 7 - Impacts of Intelligent Networks and New Services”, IEEE Journal on Selected Areas in Communications, Vol. 12, No. 3, pp. 501-509, 1994.

[3] L. Angelin, S. Pettersson and Å. Arvidsson, “A network approach to signalling network congestion control”, Proceedings of the ITC Seminar in St. Petersburg, 1995.

[4] L. Angelin and Å. Arvidsson, “A Congestion Control Mechanism for Signaling Networks based on Network Delays”, Proceedings of NTS-12 in Helsinki, 1995.

[5] P.J. Kühn, C.D. Pack and R. Skoog, “Common Channel Signaling Networks: Past, Present, Future”, IEEE Journal on Selected Areas in Communications, Vol. 12, No. 3, pp. 383-394, 1994.

[6] A.R Modarressi and R.A. Skoog, “Signaling System No. 7: A Tutorial”, IEEE Communications Mag., Vol. 28, No. 7, pp. 19-35, 1990.

[7] B. Jabbari, “Routing and Congestion Control in Common Channel Signaling System No. 7”, Proceedings of the IEEE, Vol. 80, No. 4, pp. 607-617, 1992.

[8] D.R. Manfield, G. Millsteed and M. Zukerman, “Congestion Controls in SS7 Signaling Networks”, IEEE Communications Mag., No. 6, pp. 50-57, 1993.

[9] S. Pettersson and Å. Arvidsson, “Economical aspects of a Congestion Control Mechanism in a Signaling Network”, Proceedings of NTS-12 in Helsinki, 1995.

[10] S. Pettersson and Å. Arvidsson, “A profit optimizing strategy for Congestion Control in Signaling Networks”, Proceedings of the ITC-Seminar in Bangkok, 1995.