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Routing Performance in Air Traffic Services Networks

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***Abstract*—Fixed alternative routing algorithms are currently used for call establishment in voice communication systems of air traffic services. Under certain conditions, the standardized routing scheme create suboptimal routing decisions. A simple extension of the currently used algorithm prevents routes from being selected during call setup, if the particular route has recently been used for an unsuccessful call setup. The modification solves the stated routing problem and its performance is compared with other dynamic algorithms.**

I. Introduction

The paper discusses characteristics of certain dynamic routing algorithms and their applicability to a specific communication system which is used for ground-to-ground voice communication in air traffic services (ATS) networks. Routing in these circuit switched networks is currently performed by fixed alternative routing (FAR) algorithms with a predefined order of direct and alternative routes. That simple algorithms however suffers from a specific problem which decreases the number of successfully established calls when experiencing multiple simultaneous failures. Beside evaluation of different routing strategies, the authors present a simple extension of a FAR algorithm which solves the stated problem and attempts to satisfy the stringent requirements of dynamic routing in air traffic services networks.

Dynamic routing algorithms have been used in telecommunication networks for a long time [1]. Many conceptually different classes of routing algorithms with varying attributes and characteristics have been developed. While the impact of dynamic routing algorithms has declined during the last decade due to emerging packet switched technologies which demands for different routing requirements, the increasing demand for traffic engineering and quality of service for end-to-end communication in these networks led to a recurrence of these traditional concepts.

The paper illustrates the performance of different dynamic routing algorithms in loosely meshed topologies by the means of simulation. A simplified model of the communication network is used to create data for different algorithms and parameters.

II. Technological Requirements and Restrictions

Communication networks for air traffic controls demand in particular for simple and reliable solutions. The International Civil Aviation Organization (ICAO) proposes the digital signaling standard ATS-QSIG [2] as replacement for legacy analog signaling technologies [3]. ATS-QSIG is a functional profile of the private signaling system Number 1 (PSS1) [4]. The protocol standard PSS1 is a suite of standards for private branch exchanges (PBX) in integrated services digital networks (ISDN). Hence, both PSS1 and ATS-QSIG refer to concepts and the terminology found in ISDN. However, ATS-QSIG implements only a subset of the functionality of PSS1 while adding several supplementary services specifically developed for the requirements of air traffic services like call priority interruption and call intrusion. In contrast to traditional fully connected cores of circuit switched telecommunication networks, ATS-QSIG infrastructures were generally built from loosely meshed topologies, that in general corresponds to geographical conditions of a particular region. A link consists usually of several 64kBit/s lines with a guaranteed quality of service. The data rate of these links is multiplexed in three voice and one signaling channel. Signaling messages for establishing voice communication paths between sender and destination are created on a circuit-switched basis via hop-by-hop routing. PSS1 and ATS-QSig define state machines and signaling messages used for call establishment.

ATS-QSIG defines a simple mechanism for avoiding infinite loops in case of weak routing decisions under situations of multiple failures. Similar to the time-to-live field for Internet protocol packets, ATS-QSIG defines the so-called transit counter (TC), which is part of the initial signaling message. The TC counts the number of network nodes passed through during call setup. If the number exceeds a particular value, tantamount to reaching the maximum path length, the call is regarded as lost and cleared. The value of the transit counter is network specific and basically depends on the network diameter.

The structure of ATS networks fundamentally differs from telecommunication networks. ATS networks are smaller and provide only a few air traffic controller access to the network. Another important difference is the generous capacity of ATS networks. Since availability is of major importance for air traffic services, sufficient network capacity is provided to cope with peak loads under normal network operation. That means ATS networks are designed to be non-blocking.

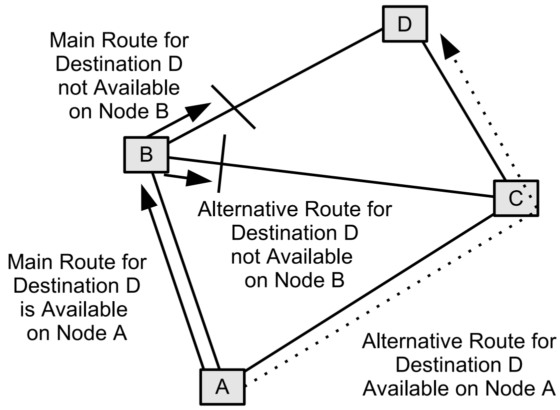

Fig. 1. Exemplary problem of fixed alternative routing (FAR) in ATS-QSIG. Although a path between network node A and node D via node C is available, the FAR forces A to route a call to network node B, where the call can not be routed any further.

The ATS-QSIG standard suggests a simple, but stable fixed alternative routing algorithm. For every destination, a routing table defines one direct route, which is always chosen if sufficient resources are available, and up to 5 alternative routes which are tried consecutively if the direct route cannot be used. The priority interruption concept of ATS-QSIG furthermore provides the ability to cope with prioritized call attempts. If the direct route for a particular destination is not available due to congestion on the link, the routing algorithm attempts to interrupt some low priority call on the direct route before routing the call along an alternative route. Besides routing calls over the link from which the call was received, there are no further rules implemented in the routing algorithm.

One benefit of the implemented routing scheme are fast call setup times. Every network exchange can easily determine the subsequent network node and is exempted from performing complex route calculations. Furthermore no routing information must be exchanged between network nodes, since the routing tables are manually configured and do not change dynamically in response to particular network conditions. This determinism however also leads to problems under situations of multiple failures.

As shown in Figure 1, the routing algorithm, which is suggested by the ATS-QSIG standard, creates suboptimal routing decisions when several network links fails. If, as illustrated in the example in Figure 1, the direct route leads to a network node where neither direct nor alternative routes can be used for routing the packet further towards its destination, the call is cleared. If the link conditions do not change, any following call attempt will be cleared in the same manner, since there is no dynamic mechanism in the routing algorithm preventing the network node from using its preferred direct route.

The impact of this problem on the overall system is diminished by solving it on other network layers. E.g. if call establishment fails, the voice application automatically redials the same number several times or external dial-up connections are established after the first call setup terminates unsuccessfully. However, shifting the responsibility to other parts of the system increases their complexity, although the problem is basically caused by the localized attitude of the fixed routing decision with insufficient information about remote link outages.

There are several intuitive options how to solve this problem. Thus before discussing the improved algorithm, the next chapter defines the scope of the application domain and discusses different solutions and their relevance for air traffic services.

III. Constraints for Routing Algorithms

Certain concepts of different routing algorithms seem to provide an immediate solution for the routing problem described in the previous chapter. However, the impact of routing decisions on the performance of the overall communication system implies several restrictions. The functional requirements for ATS networks and the commitment to ATS-QSIG as signaling standard complicates the use of several algorithms and technologies.

The FAR algorithm which is currently used bases all decisions on a manually configured, predefined lists of preferred routes for every destination. The claim for simplicity inhibits the implementation of a highly dynamic algorithm which periodically exchanges routing information. The research therefore focused on the extension of the currently used functionality.

For evaluation, all routing algorithms have been implemented in a discrete event simulator. The model uses a detailed description of the state machines with 7 of the most important signaling messages of ATS-QSIG to maintain connections between sources and destinations. The main purpose of the simulator is to perform tests of the routing capabilities of different algorithms. Test data was created by simulation runs of 100.000 calls for 10 and 20 different network loads for each algorithm. Every point in the resulting graphs (as e.g. Figure 2 represents the mean of independent 8 simulation runs.

A. Dynamic Exchange of Routing Information

One possible solution for the problem illustrated in Figure 1 is the mutual exchange of routing information. If network node A would be aware that routing towards node D from node B is not possible, it would send the call immediately to node C. So why not simply disseminate routing information in the network about the state of the links or other potential problems?

Besides the low data rate of 16 kBit/s for the transmission, which must be shared with all other signaling messages, inevitably timing constraints and delays, prevent meaningful exchange of routing data to create a decentralized global information base about the status of the network. In general there are two different causes which hinder a node from sending a signaling message to a particular neighbor: link failures and link congestions.

Link failures are rare events and network operators are responsible for building their network from an infrastructure which is able to cope with several error conditions. If a link fails, it takes a small period of time until the connection is operational again, either by repair or by diverting connections onto different on lower physical layers.

In contrast to physical link outages the durability of routing problems due to congested links is much more transient. Link congestion is not supposed to occur very frequently under normal operation due to sufficient network capacity in ATS networks. However, in combination with solitary link failures and the resulting decrease of network performance, transient congestions may occur more common. Calls in air traffic services usually last for some 10 to 15 seconds. So even if occasionally a link is not available due to some short term overload conditions, after a very short period of time, there is a high probability that the routing algorithm will be able to use that particular link again.

For routing algorithms which permanently exchange information about network status, both link failure and congestion may cause routing updates to be distributed within the whole network. For long-term link failures this may make sense. For the more common short term congestions, the costs, in terms of network resources, for distributing the routing updates, are too expensive.

Beside timing constraints for distributing routing updates within the network, it is also important to consider the computational time of a routing algorithm necessary to determine a correct route. Since call setup times are crucial, long delays caused by routing updates and complex route calculations can not be tolerated. The magnitude of delays caused by dissemination of routing updates is however much larger than reasonable route calculation. Currently, the routing algorithm guarantees a simple worst case delay by providing a list of several routes which are probed in sequence, without interfering with any adjacent nodes or complex route calculation.

The installation of a separate infrastructure which handles routing updates is, because of the resulting additional costs, no option. Routing algorithms which exchange information about network states among each other are currently state of the art in packet switched networks. Any explicit transmission of routing data in ATS-QSIG networks increases the complexity of the application running on the network exchanges. These systems however shall stay simple and understandable. For air traffic services networks which use ATS-QSIG, algorithms which base on the global exchange of routing data are a suboptimal solution. However further research on localized routing updates is currently under way.

B. Crankback

Another potential solution for the routing problem depicted in Figure 1 is the use of crankback. Crankback describes the ability of a network to reissue a failed call attempt on a preceding network node: If a network node cannot route a call any further due to insufficient link capacity or link failures, the call is cleared and a corresponding messages is sent back to the source of the call. Under the use of crankback, a preceding node can reattempt to forward the call on another, previously not chosen route. The idea is to simply search for more than one path, if one particular route leads to a dead end.

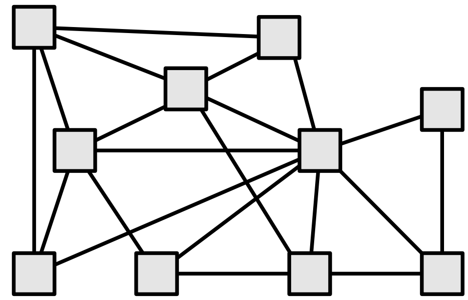

Fig. 3. The loosely connected 10 node network used for the simulation. All links provide the same data rate.

Crankback is a potential solution for the stated problem in ATS-QSIG networks. However the algorithm introduces much complexity into the communication systems. Whenever crankback is used during call setup, more network resources are consumed for a short time due to dead end paths. A lower number of available channels for other calls might hinder further calls from being established successfully.

A similar problem occurs when routing paths along alternative routes in general. Every time a call cannot be forwarded on its direct route, the routing algorithm is forced to establish calls over an alternative route. However, alternative paths are in general longer compared to connections along direct paths. The augmented resource consumption may increase congestion on these evasion links even further. It depends on the network layout, how often links are congested and how many failures a network is able to cope with.

The increased resource consumption of dead end paths when using crankback is, because of their transient nature, marginal compared to the fraction caused by the increased path length due to longer alternative routes. However, using crankback always incorporates alternative routes, since the direct routes have been unavailable before.

One possibility to damp the effects of crankback is to restrict the number of nodes where crankback is used. On the one hand this decreases the network load, since fewer potential paths are evaluated during call setup. On the other hand, the probability to successfully find a path also drops. In the simulation, the transit counter of ATS-QSIG indirectly restricts the maximum number of times, crankback is used for a single call.

For this paper several values for the maximum crankback attempts are tested. All routing algorithms benefited from using crankback as illustrated in Figure 1. However the differences how many times crankback is allowed in a single call are negligible. The tests were performed with the network depicted in Figure 3 which consists of 10 nodes. Crankback increases the amount of successfully established calls. The next section discusses further network parameters which were evaluated for their applicability in ATS networks.

C. Usage of Popular Network Parameters

Dynamic alternative routing (DAR) is a dynamic routing algorithm which is similar to the FAR algorithm recommended by ATS-QSIG. DAR uses, except for the direct route, one

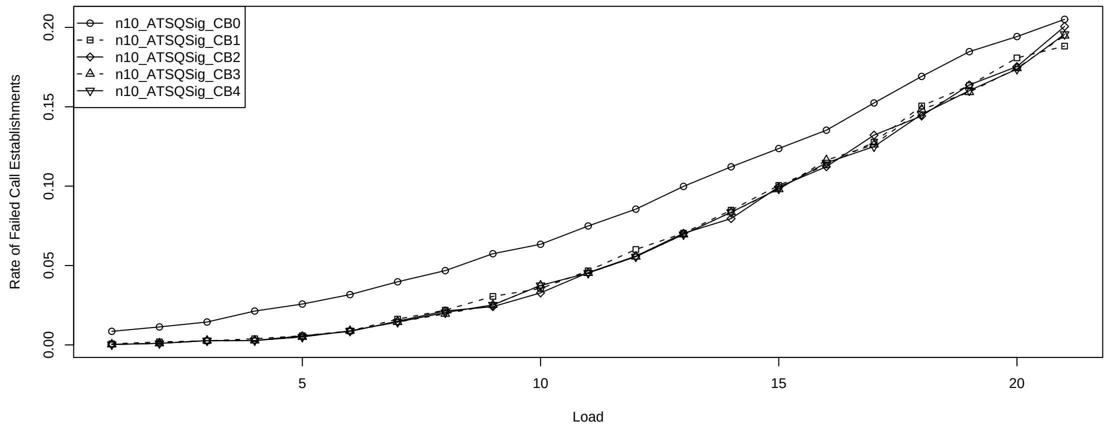

Fig. 2. FAR with crankback outperforms FAR without crankback in a loosely meshed network. The illustrated numbers have been calculated for the network displayed in Figure 3. The x-axis of the diagram represents the network load. On the very left, the network is already saturated, however nearly zero calls were lost. By further increasing the network load, the rate of failed calls raises. The parameters CB1 to CB4 indicate the maximum number of times crankback is used for a single call setup.

preferred alternative route which is always used for routing if no channel is available on the direct link. If this preferred alternative is not able to route a call too, alternative is chosen randomly out of a pool of all alternative links. If the call can be routed along this previously selected route, it becomes the new preferred alternative. The routing algorithm introduces two interesting features: non-determinism for alternative route selection and sticking to this decision as long it is able to route a call successfully.

DAR has been developed for fully connected telecommunication networks [5][6]. Though the basic algorithm performs well under regular network conditions, it experiences one potential flaw under high load situations. This conceptual problem can however be diminished easily by introducing a network parameter that limits the use of non-direct traffic on direct connections. Under high load situations, the direct routes are not able to carry all traffic, thus more calls are routed over alternative routes. In fully connected networks, alternative routes are always longer than the direct routes. Massive use of alternative routes decreases the network capacity further. This results in even more direct routes getting occupied with alternative traffic. There is however a simple and stable concept called trunk reservation which prevents this situation.

Trunk reservation (TR) damps the effects of massive alternative routing under high load conditions by granting a small amount of link capacity exclusively to calls along direct routes [7]. A very small fraction of about 5 to 10 percent of all channels on a link is sufficient for stabilizing the network performance even under high network loads.

TR is currently not implemented in any form whatsoever into ATS networks. One problem with simply applying TR to ATS networks is, that preventing a call at a certain node in a meshed network would decrease the rate of successfully established calls under high load situations. Failures and congested links would not be the only possibility anymore that hinder a call from being successfully routed on an alternative link any more. Also insufficient link capacity on alternative routes caused by TR would prevent links from being chosen. Though the network performance benefits under overload situations, high network load would further increase the problem depicted in Figure 1. Another problem is that voice communication systems in air traffic services are quite small compared to large telecommunication networks. Depending on the actual structure of the network, the capacity on each link is generally low. So the question arises what is a reasonable number for reserved trunks in networks with a low number of channels on every link.

As illustrated in Figure 4 DAR performs well in fully connected networks. Actually DAR with trunk reservation enabled performs excellent in these networks. However due to the randomness of route selection the results in general loosely meshed networks are worse compared to FAR (see Figure 6). The problem of DAR in non-fully connected networks is, that the selected routes do not consider the direction where the destination is located. Routing to random alternatives ruins the performance of DAR with and without the usage of trunk reservation. In fully connected networks, establishing calls on randomly chosen alternative routes is not a problem, since all nodes are immediate neighbors. In general topology networks, the direction of alternative routes is an issue.

IV. Prohibitive Routing

Dynamic exchange of routing data is no useful option for ATS networks. The loosely meshed characteristics inhibit DAR from being as effective as in fully connected networks. Though crankback provides a potentially good solution for the problems illustrated in Figure 1, an implementation also incorporates major changes, not necessarily limited to the routing subsystem.

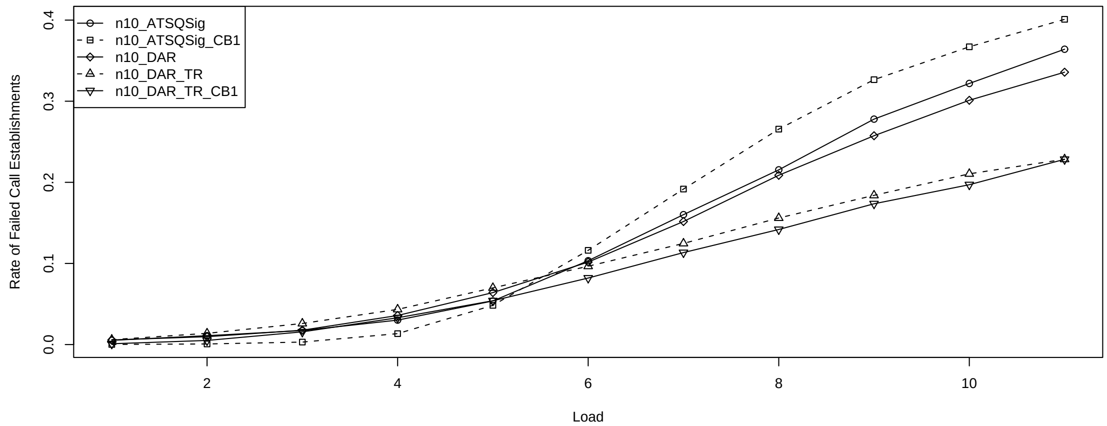

Fig. 4. DAR benefits from trunk reservation in a fully connected network with 10 nodes. The impact of crankback for DAR is marginal. DAR without trunk reservation performs better than FAR, yet comparable.

This paper therefore presents another solution for the given problem. A routing algorithm which prohibits routes from being chosen for a short time if a previous call attempt for a particular destination has recently failed. The algorithm is called prohibitive routing. The paper also describes one moderate variant called enhanced prohibitive routing algorithm. Both are extensions to the FAR scheme and therefore maintain one direct route and a list of alternatives.

The basic idea of prohibitive routing is to avoid the selection of routes which have recently been part of unsuccessful call attempts. In ATS networks it seems rational that the routing algorithm prohibits the use of routes which experienced transient failures, since most calls have a short duration and solitary peak loads will not last for long. Permanent connections or potentially longer calls are statically incorporated into the network configuration.

Without the use of crankback, prohibitive routing does not immediately produce better results for a single call. The first, unsuccessful call creates a clearing message which causes the prohibitive routing algorithms in all nodes to evaluate whether or not to prohibit the selection of a particular route. Without the use of crankback, that first call is cleared. But all subsequent calls with the same destination which are sent shortly after the first unsuccessful call, will be routed differently, since some routes are closed by the routing algorithm. Prohibitive routing solves the problem described in Figure 1 by temporarily altering the routing tables.

In order to prevent the prohibitive routing algorithm from banning too many routes, two different mechanisms apply. One simply considers where the call setup has failed, while the other prevents that all or too many routes become unavailable.

Every clearing message contains some information about the reason why the call has been cleared. ATS-QSIG differentiates 32 different clear causes for regular and abnormal call clearing. Nodes in the path which evaluate the clear cause know why call setup has failed, however they do not know exactly where the problem occurred. No such information is part of the standard clearing messages.

ATS-QSIG however provides the possibility to add small amounts of diagnostics data to every clearing message. Hence, more comprehensive information than the solitary clear cause can be transmitted backwards to the source node. The prohibitive routing algorithm uses that diagnostics data for transferring information whether or not to prohibit particular routes at preceding nodes. Only nodes close to the origin of the problem restrict the usage of routes. This increases the total number of available paths between originating and terminating node.

Besides this incorporation of auxiliary routing data, the second mechanism, that prevents too many routes from being banned, defines a threshold for the maximum number of prohibited routes on every node. Every time the routing algorithm prohibits the use of a route due to another failed call establishment, the node evaluates whether there are still sufficient available routes present. If the maximum number of banned routes is exceeded, the route which has been prohibited for the longest time, will become available again. Different values how long a route stays prohibited have been evaluated. Currently this prohibitive time (PT) is equal on all nodes and has been set to 7 for the simulation.

Figure 5 illustrates the behavior of prohibitive routing with two examples. For simplicity, assume that fixed routing tables of the example have been configured using a shortest path algorithm.

An extension of the basic algorithm, the enhanced prohibitive routing, attempts to minimize network usage in situations when the call success rate is decreasing because of high network load or link failure. It works in principle like the regular prohibitive algorithm for normal network situations. The only difference is the existence of a ring buffer which is used to record the success rate of the last n calls. A flag in the buffer indicates whether a call has reached its destination

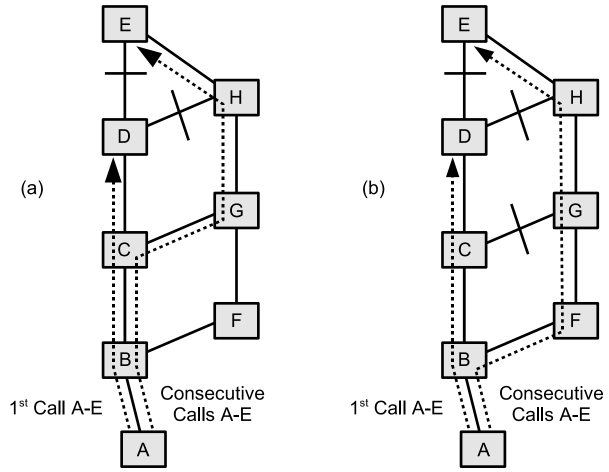

Fig. 5. Two examples for prohibitive routing: (a) On the left side, node A initiates a call to destination E. Node D is not able to route the call any further and initiates call clearing. By processing the received clearing message, node C prohibits, for a short time, future calls with destination E from using the link to D. Since there is one route (G) available to route calls which come from B onward to E, node C removes the routing data from the clearing message before forwarding it to B. Node B simply continues call clearing. Consecutive calls from A to E will be routed via node C and G. (b) The second example illustrates the case when at node C no other route is available for destination E. Imagine link C-G experiencing some transient overload situation. Since immediately routing back on the incoming link is not allowed, C prohibits the use of the route to D, but does not remove the diagnostics data from the clearing message. This causes node B to evaluate the routing data of the clearing message and to prohibit the route to C. Consecutive calls from A to node E will be routed via node B and F.

or no route has been found.

When, at a particular node, the number of unsuccessful call attempts is increasing above a certain level L, the node only uses those alternative routes which length results in paths that are at most of the length of the direct route. The length of direct and alternative routes is calculated when setting up the routing tables at start up.

The idea is, that in a situation of low network performance, any additional, unnecessary load will further deteriorate the situation. Instead of reserving a lot of the precious network resources by using long alternative routes a call is only routed over the direct route or over a short alternative route.

V. Conclusion and Further Work

The paper compares the performance of several dynamic routing algorithms and their parameters in the application area of air traffic services networks. Communication systems which implement the routing algorithm proposed by the signaling standard, suffer from performance penalties when multiple failures simultaneously occur in the network. The authors suggest an extension for the currently used FAR algorithm which restricts route selection for a short time for future calls when the route has participated in an unsuccessful call establishment.

FAR algorithm performs well under high load situations. DAR performs poor in loosely meshed networks, especially when used in combination with trunk reservation. The results of DAR might benefit when alternative route selection is not based on independent random values, but reflects the structure of the network to some extent. The prohibitive routing algorithm, which is able to solve the problem illustrated in Figure 1, and FAR, without the use of crankback, deliver comparable results. Since the implementation of crankback in ATS networks includes complex modifications on several system layers, prohibitive routing seems to be a reasonable solution for the stated problem.

The performance of the enhanced prohibitive routing algorithms is poor. With the intention of increasing the performance of basic prohibitive routing by restricting too long paths under overload situations, this result is unsatisfying. Future work will inspect the reasons for this behavior in more details.

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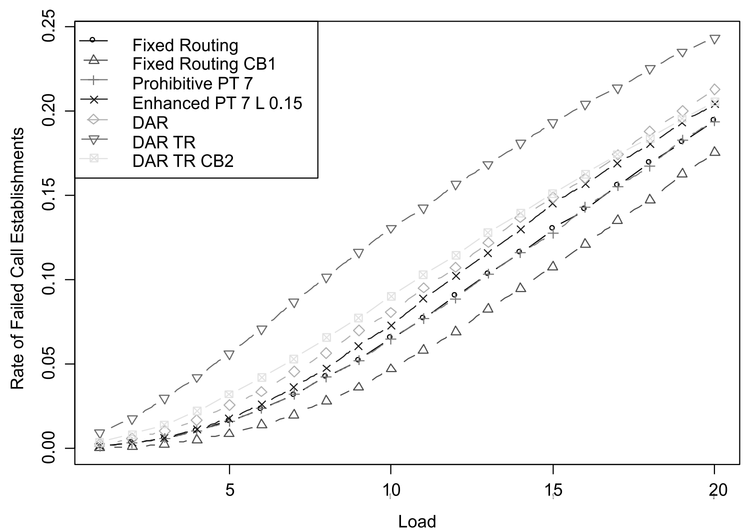

Fig. 6. In the 10 node network, the best performance, in terms of successfully established calls, is achieved by the fixed routing algorithm with crankback (Fixed Routing CB1). Fixed and prohibitive routing algorithms (Prohibitive Timer PT is set to 7 seconds) perform comparable under high load situations. Enhanced prohibitive routing (Level L is set to 0.15) performs worse, however still better as any simulation run with DAR (basic DAR, DAR with trunk TR reservation, with and without crankback CB2).