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Published in:
Proceedings of the 16th IST Mobile and Wireless Communications Summit

DOI (link to publication from Publisher):
10.1109/ISTMWC.2007.4299301

Publication date:
2007

Document Version
Publisher's PDF, also known as Version of record

A New Selection Metric for Backup Group Creation in Inter-Vehicular Networks

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***Abstract*—Reliable service provisioning in car-to-car networks is challenging because the environment is very dynamic and network topologies are changing rapidly, hence making communication unreliable. For service-level fault-tolerance, the service needs to be replicated onto several vehicles. For state-full services with dynamically changing state, a careful choice of the replica servers is necessary due to the dynamically changing properties of the communication paths between them. This paper proposes and analyzes a heuristic metric called geo-cost that aids the selection of replica candidates based on information about speed and direction of the cars. The analysis in simulation experiments shows that the proposed heuristic is performing equally well when compared to an existing approach based on a snapshot measurement of network delays. The difference between the existing metric and geo-cost is the feasibility of geo-cost compared to network delays that are often hard to determine furthermore the lifetime of the groups will be increased. Obtaining the geo-cost metric will consume considerably less power than obtaining end to end delays.**

***Index terms*— state-sharing, dependability, inter vehicle communication, dynamic reconfiguration.**

I. Introduction

Future automotive traffic will make increasing use of car-to-car communication. We foresee that as ad-hoc communication protocols mature, many applications building on the car-to-car network will emerge [1], [2]. Some of those will require high dependability because they are of safety critical nature, such as automated highway systems [3]. One fundamental approach is based on utilizing replication: In case there is a failure in the original, a replica can be used. For applications that are state-full, replication not only requires running several instances of the application the network but also state updates has to be communicated between the replicas. There are several approaches for state sharing [4], [5]. There is a risk that long delays or packet loss results in an inconsistent state of the replica [6]. Another influencing factor is the way state updates are sent. In this paper it is assumed that the transmission of the state update is done immediately after state changes. In vehicle-to-vehicle communications an all-to-all state replication mechanism is not scalable, therefore replica groups need to be formed on-demand. For instance, in a traffic jam the density of cars may be so large that letting all cars backup their application state data on each other will flood the network. For an environment as dynamic as car-to-car networks, locking mechanisms or commitment protocols are infeasible. Hence for this paper the case of persistent backup is assumed and the state replication strategy is optimistic. The replica group selection can be made more efficient when utilizing group mobility: Since cars are bound to drive on roads, in particular in rural settings and free-way scenarios lower network delays and longer group lifetimes can be achieved when selecting nodes which travel in geographic closeness and in the same direction, with similar speed.

For the criteria: minimizing the end to end delay between all nodes in the group, the task of determining an optimal partition of the ad-hoc network in replica groups is algorithmically difficult (np-complete), so that heuristic algorithms need to be utilized, see [7]. The algorithms in the latter reference were analyzed assuming (snap-shot) knowledge of the network delays, which in practice are hard to obtain, since they would require periodic measurements of round-trip times between all pairs of nodes in the ad-hoc topology.

Assuming that cars carry GPS receivers, reasonable accurate positioning information is available (locally in the nodes) as well as information about speed and driving direction. This information can be exploited as a new geo-cost metric for replica group formation, as presented in this paper. This paper represents a step in the direction of distributed group management based on metrics that can be measured with little effort.

The rest of the paper is organized as follows: In Section II the scenario will be described. This description will be followed by Section III where the new geo-cost metric is defined which is input for the group-formation algorithm. Section IV defines the parameters for the evaluation and methods for result comparison. Section V presents an analytic analysis of the simulation results. In Section VI the results of the simulations are discussed. Finally Section VII concludes the paper and gives an outlook on future work.

II. Scenario Description

The scenario investigated in this paper consists of cars travelling on roads, as illustrated in Figure 1 for an urban scenario. As an example of a service with high-availability requirements, we assume a black box service similar to the black box in planes. A car keeps internal logs of dynamically changing data, e.g. sensor data. This data can be retrieved by authorities in case of an accident. Instead of building a durable black box that can sustain an accident the sensor data is stored in other cars. An alternative is to upload the data via GPRS

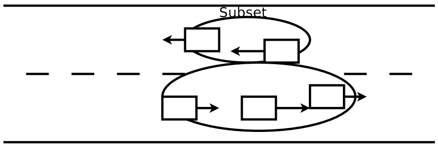

Fig. 1. Picture of the scenario.

in a central server in the Internet but that is very costly. In the scenario described here all cars act as servers and replicas by receiving backup data from other cars and sending their own data to replica cars. The partitioning in different replication subsets is done on medium to long time-scales, in order to keep the effort for subset reconfiguration low. We assume here for simplification that there is a centralized entity, placed in the Internet which controls the subset division. In future works distributed grouping will be investigated. All cars send their updated position information to the controlling server regularly and the server calculates new subsets if necessary.

If there is an accident and the black box data from the cars in the accident is needed it can be retrieved from their respective group members. The group membership can be retrieved through the central server that receives the updated position, direction and speed of the individual cars with regular intervals. In order to keep the management effort of these replications low, and in order to allow for efficiency improvements via accumulation of messages, the approach here is that the overall set of nodes in the ad-hoc domain is partitioned into disjunct subsets which perform data-replication internally in the subset. Heuristic algorithms to perform such a subset partitioning have been proposed and analyzed in [7] where the subsets were chosen to minimize the sum of the communication delays within the subset.

The state of the application is modeled as a counter, the counter value is growing with each state change. State updates are sent reactively when the process state changes. This means that the state in the replica servers is inconsistent in the period it takes to create a state update message at the master, send it and process it at the replica. So the processing time at the master, the replica and the end to end delay determines the probability of observing inconsistency[8].

III. Metrics for Subset Creation

The subset creation scheme proposed in this paper uses a division algorithm to divide the servers into state sharing groups. In [7] such algorithms were analyzed, assuming knowledge of the end-to-end delay between each node pair. Obtaining the delay information however, introduces some overhead as discussed in Section VI. For the purpose of subset division based on easily available metrics, a heuristic geo-cost metric is proposed that is determined based on the position, direction and speed of the nodes. The geo-cost metric will favor nodes that are geographically close and that belong to a group of nodes moving jointly in approximately the same direction at approximately the same speed. Although geographic closeness does not necessarily imply short path-lengths in a multi-hop topology, it is clear that a path spanning a distance in order of several transmission ranges implies more hops than a path spanning one transmission range. By also taking the speed and direction of the nodes into account the heuristic aims at stabilizing the group configuration.

In the proposed solution all servers are sending information about their speed and position to the controlling server, in regular intervals. The controlling server updates a geo-cost matrix $\overline{C}$ when the information arrives.

In the following the process of forming the replica subsets is explained. The formation of subsets is done with a heuristic approach based on the geo-cost metric. It is assumed that all cars have sent at least one message to update their speed, direction and position to the controlling server. The controlling sever calculates the distance, written as $d_t(i,j)$ in (1), between the cars i and j. The distance between the cars is projected Δ seconds into the future, written as $\tilde{d}_{t+\Delta}(i,j)$ in (1). The instantaneous and the future distances of the vehicles is summarized in a single geo-cost value for each node-pair, accumulated in the (here symmetric) matrix $\overline{C}$:

$$\begin{aligned}\overline{C}_{i,j} &= d_t(i,j) + \tilde{d}_{t+\Delta}(i,j) \\ &+ \mathrm{sign}\big(\tilde{d}_{t+\Delta}(i,j) - d_t(i,j)\big)\cdot\omega\end{aligned} \tag{1}$$

In the following the ω in (1) is selected to be 0.25 in order to emphasize the projected change of the distance if the distance is increasing. This means that the geo-cost is higher if the nodes are moving away from each other than if the nodes were to keep the current distance. $\overline{C}$ is the input to an algorithm that forms subsets such that the sum of the cost-values between node-pairs in a subset is minimized.

IV. Simulation model

To evaluate the geo-cost definition a simulation tool is developed that simulates network behavior. This simulation is an abstraction of actual network behavior where an end to end delay distribution is derived from the path-length in the current network topology.

The simulation uses an initial random node-placement on a single road, 300 meters wide and 2000 meter long wrapped around a cylinder to avoid edge effects. Calculating the distance between the cars takes this into account so that it is always the shortest way around the cylinder that counts as the distance.

The road has two lanes. The traffic is in one direction in one lane and in the other direction in the other lane. Although communication links show variable transmission delays as described further below, the maximum transmission range is assumed constant (300m).

The simulator is a discrete event simulator with periodic updates of the topology information. The topologies are created in series of 200. Each of these topologies within a series is referred to as a step. For each step the nodes are moved according to their speed and direction and the amount of time between each step.

In order to get sufficient inconsistency data samples for statistical analysis the time interval between two position

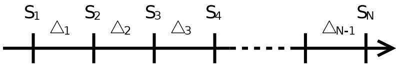

Fig. 2. Time line with simulation steps and time increments.

updates is simulated a number of times. Each time interval is stretched until 8000 state updates have been sent.

For the initial topology the coordinates as well as the speed of the nodes are selected from a uniform distribution (the latter with maximum 30 $\frac{m}{s}$ which amounts to an approximate highway speed), while the movement direction is a consequence of the lane that the node is placed in. The initial topology is drawn until a topology is created where there are no disconnected nodes. For each simulation the parameters that can be varied are:

- Time between steps: δ_t
- Number of servers: N
- Maximum speed: v_{max}
- Initial transmission delay: D_0
- Retransmission delay: D_r
- Hop penalty (processing delay in relay nodes): D_h
- Maximum transmission range: R_{max}

The initial coordinates are then used for the replica subset partitioning in two different ways:

1) Delay based costs: a network topology graph is formed based on the maximum transmission range and the node coordinates. The (undirected) edges of this graph are labelled with transmission delays as obtained from a link model described further below. For each node pair (i, j), a path with shortest hop-count is computed and the corresponding link delays are added up and stored in the cost matrix.
2) Heuristic based on distance, speed, and direction: as described in the previous section. For each node pair (i, j) the geo-cost value is determined according to Equation (1) and saved in the cost matrix.

After the cost matrix has been determined, the heuristic SOPCS algorithm from [7] is used to form the partition of the nodes into replica subsets of constant size (here of size 4). Then the actual network simulation starts, simulating replica update messages with appropriate network delay, measuring inconsistency between the master node and its replicas. Figure 3 shows an overview of the overall approach for the two cases.

New black-box data is assumed to be available at the master node here the time between data generation is distributed according to a Poisson process with rate $1Hz$. Upon these events, update messages to all replica nodes in the subset are triggered, which arrive at these nodes after a delay influenced by the number of hops in the path and the properties of the individual link. The end to end delays are determined for each node pair along with updated positions before starting to simulate each step. When generating state update messages the delays are looked up in a pre-calculated table.

Since the geo-cost metric also takes predicted changes into account, it is expected to perform better in the cases where the nodes are mobile.

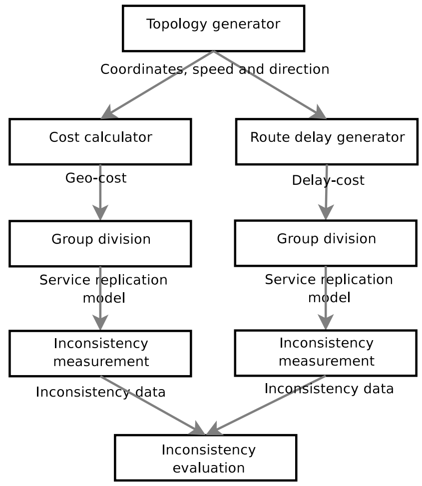

Fig. 3. Block diagram of the evaluation software.

A. Multi-hop Network model

The wireless network is modelled as follows: The end to end delay is a sum of the individual link delays on the multi-hop path. It is assumed that there are no collisions on the wireless medium and that the packet size is constant. However, packet-error can occur on a link level transmission between nodes. The error probability is a function of the geographical distance between the nodes based on the transmission range of 802.11abg equipment, eg. 300m. Due to the use of (infinite) link-layer retransmissions, such unsuccessful transmission attempts lead to longer link-delays.

The received transmission power (P_r) follows the standard path-loss equation, where the path-loss exponent $\gamma = 2$ is used:

$$P_r[dB] = \begin{cases} 20log_{10}(C \cdot d^{-\gamma} \cdot P_t) & \text{if } d \leq 300m \\ 0 & \text{otherwise} \end{cases} \tag{2}$$

The used transmission power (P_t) is 15 dBm for a typical 802.11ab card. The parameter C is chosen so that at 300 meters the resulting $BLER$ from (3) is 60%; at larger distances the $BLER$ is 1.

The packet loss probability is a function of the received signal power, which here for simplicity is assumed to be exponential:

$$BLER = \begin{cases} e^{-k \cdot P_r} & \text{if} P_r[\text{ dBm}] \geq 0 \\ 1 & \text{Otherwise} \end{cases} \tag{3}$$

See Eq. (9) in [9] for validity of this exponential approximation. The drop-off rate is set to $k = 0.31$, to achieve a realistic range of packet error rates.

Using a simple retransmission approach, namely repeating the transmission attempt on the link until successful, and assuming independent packet errors, the number of transmission attempts is geometrically distributed with parameter $BLER$, and the expected delay for a single link is:

$$D = D_0 + D_h + D_R \cdot \frac{BLER}{1 - BLER} \tag{4}$$

where D_0 is the duration of the first transmission attempt, and D_R is the time needed to detect the unsuccessful transmission and to perform a retransmission. D_h is the processing delay added by a forwarding node. Where nothing else is specified the simulations reported here uses the following values:

- Delay for first transmission attempt: D_0=50ms.
- Retransmission delay:D_R=80ms.
- Hop penalty: D_h is varied between 10ms and 60ms.

V. Analytic Analysis of Inconsistency Probability

In [6] timely remote-access to dynamically changing information elements is analyzed analyticly. The calculation of the so-called mismatch probability for the proactive event-driven information access in that reference corresponds to the inconsistency metric as used here. However, the analytic solutions in [6] only apply in the current form to server sets of size two. In that scenario, and when the changes of the application state occur according to a Poisson process (as assumed also in the previous analysis of this paper), the inconsistency or mismatch probability can be calculated as:

$$P(\texttt{incons}) = 1 - e^{-\lambda D} \tag{5}$$

Thereby λ is the rate of the Poisson process of state changes and D is the expected value of the end-to-end delay between the two servers. This formula holds not only for deterministic end-to-end delays, but for any delay distribution with finite first moment of size D, if the state-updates use an incremental approach, i.e. only carry differences to the previous state-value (which is monotonously changing).

This analytic expression can be used to validate the simulator, e.g. for a state-change rate of $\lambda = 1$ and a certain node distance corresponding to a 1-hop transmission delay of $D = 0.1524$, both the estimated inconsistency and the analytic formula yield the value of 14.14% for the inconsistency.

Beyond the validation of the simulations, the analytic formulas and insights from [6] can also be used to discuss scenario modifications, in particular, the actual type of distribution of the end to end delay is not relevant for inconsistency in the scenario of subsets with only two nodes (even if they communicate in a multi-hop fashion, which according to the wireless model of Section IV-A results in the convolution of appropriately scaled geometric distributions). Extensions of the analytic mismatch calculations of [6] for scenarios of subsets of larger size are for future study.

VI. Discussion of Evaluation Results

Figures 4 and 5 show the measured inconsistency levels for two experiments with the same initial topology and the same delay settings. In Figure 4 the subset division algorithm was given up to date metrics which allowed the algorithm to reconfigure the subsets whenever needed. For every step in the simulation the subset division algorithm was executed. The circles in the graph mark the simulation steps when the results of running the heuristic algorithm was different compared to the previous step. In Figure 5 the algorithm was given the

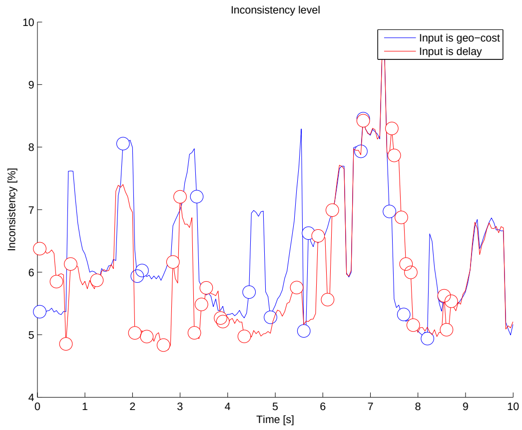

Fig. 4. Plot of average inconsistency level for 200 topologies. Initial delay 50 ms, retransmission delay 80ms, processing delay in relay nodes 30ms.

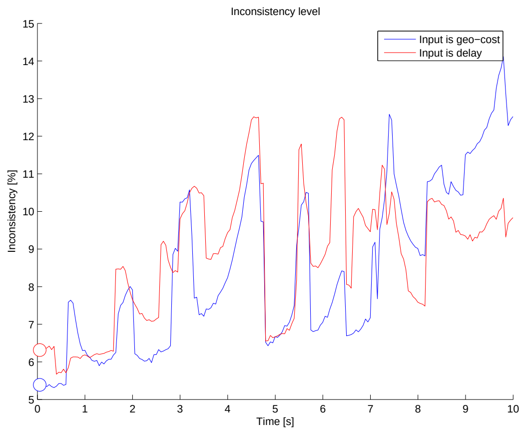

Fig. 5. Plot of average inconsistency level for 200 topologies of 48 servers. Initial subset configuration is kept. Initial delay D_0=50ms, retransmission delay D_r=80ms, processing delay in relay nodes D_h=30ms, $\delta = 20ms$

topology information from the beginning of the simulation. In this figure it can be seen that the inconsistency level for the geo-cost experiment is lower for the first 7 seconds.

Making a comparison of the inconsistency levels in the individual points in the graphs for the two input types is not possible since the subsets have been formed using a heuristic algorithm. This algorithm was given a heuristic input. The observation to be made in Figure 4 is that the mean inconsistency level is equal using the two input metrics.

In case of Figure 6 the geo-cost metric values generated are within a range where the SOPCS algorithm produces very good subsets. In several cases the geo-cost metric has proved to outperform the delay metric for certain topologies.

In Figure 4 the number of reconfigurations when using delay as input-metric is 13 while the number of reconfigurations when using the geo-cost metric is 30. In Figure 6 the number of reconfigurations when using delay as input-metric is 21 while the number of reconfigurations when using the geo-cost metric is 19.

In Figure 7 the mean inconsistency levels are depicted

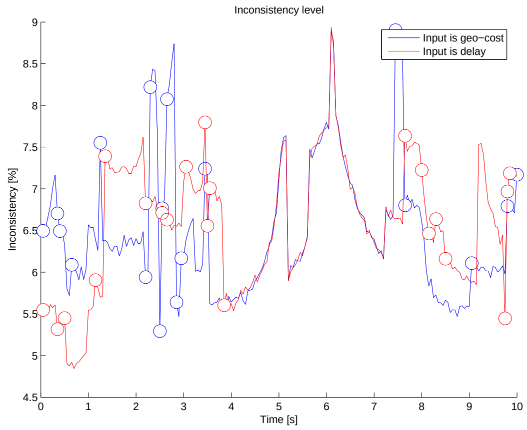

Fig. 6. Plot of average inconsistency level for 200 topologies of 48 servers. Initial delay D_0=50ms, retransmission delay D_r=80ms, processing delay in relay nodes D_h=40ms, δ=20ms.

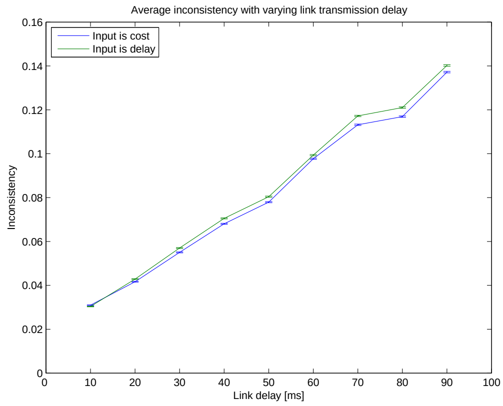

Fig. 7. Plot of inconsistency levels with varying first transmission attempt delays (1-100ms in 10ms intervals), while retransmission delay is varying proportionally (1.3 times the delay).

for different link delays, each point in the graph is the mean estimator from 20 simulation runs. Both cost functions perform almost equally well, with slightly lower inconsistency estimates for the geo-cost based approach.

VII. Conclusion and Outlook

In this paper it has been shown that it is possible to base group division on metrics that are feasible to acquire. The geo-cost metric has been shown to perform equally well as using the end-to-end delay between all nodes.

It will not be possible in a larger ad-hoc network with possibly hundreds of nodes to have up-to-date end-to-end delay information between all nodes. The measurement overhead alone would cause a significant amount of traffic and degrade the performance of the replicated application running on top.

The performance of a replicated state-full application has been evaluated with respect to inconsistency both analytically and with simulations. The geo-cost metric has shown its benefits in trying to predict the future distance penalizing nodes that will move away from the group. Thus group reconfigurations do not need to occur as frequently, which in turn reduces the amount of control messages needed.

Future work includes a detailed analysis of the time-scales at which subset reconfiguration should be performed in dynamic scenarios and inclusion of the reconfiguration effort in the simulations. Also, distributed algorithms will be analyzed which do not rely on central control for the partitioning. This together with the detailed protocols to implement such a dynamic reconfiguration will make it possible to provide a platform for improving dependability of applications in the ad-hoc car-to-car domain.

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