Connected Vehicles in Cellular Networks: Multi-access versus Single-access Performance

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Abstract—**Connected vehicles can make roads traffic safer and more efficient, but require the mobile networks to handle time-critical applications. Using the MONROE mobile broadband measurement testbed we conduct a multi-access measurement study on buses. The objective is to understand what network performance connected vehicles can expect in today's mobile networks, in terms of transaction times and availability. The goal is also to understand to what extent access to several operators in parallel can improve communication performance.**

In our measurement experiments we repeatedly transfer warning messages from moving buses to a stationary server. We triplicate the messages and always perform three transactions in parallel over three different cellular operators. This creates a dataset with which we can compare the operators in an objective way and with which we can study the potential for multi-access.

In this paper we use the triple-access dataset to evaluate single-access selection strategies, where one operator is chosen for each transaction. We show that if we have access to three operators and for each transaction choose the operator with best access technology and best signal quality then we can significantly improve availability and transaction times compared to the individual operators. The median transaction time improves with 6% compared to the best single operator and with 61% compared to the worst single operator. The 90-percentile transaction time improves with 23% compared to the best single operator and with 65% compared to the worst single operator.

I. INTRODUCTION

Connected cars and cooperative intelligent transport systems (C-ITS) can make roads traffic safer and more efficient. When vehicles collect and share information about the planned routes and the surrounding environment, it opens up for many new services and applications. Drivers can for example get early warnings about road hazards ahead [1], [2]. However, these applications require that the mobile networks can handle time-critical applications in moving vehicles. Many future C-ITS applications may require new communications systems such as 5G or a whole new infrastructure dedicated to vehicular networks based on the IEEE 802.11p standard; but until these systems are widely deployed C-ITS applications need to rely on the existing 3G/4G cellular networks. Relying on existing networks for C-ITS has been explicitly recommended by public authorities. For example, the C-ITS Platform[1] set up in 2014 by the European Commission advocates in its initial report (2016) [3] the use of the existing cellular communications infrastructure in order to foster uptake of C-ITS services, before the future deployment of short-range communications in the 5.9 GHz band described in standards such as ETSI ITS-G5. This same report recognises the many uncertainties related to using existing cellular networks for C-ITS services, including coping with latency-critical services. In its second report (2017) [4], the C-ITS Platform recommends following a *hybrid communication approach* where cellular networks are not only a temporary solution but also a complementary infrastructure to be used along other future technologies, hence confirming the long-term relevance of cellular networks for C-ITS services.

We have therefore conducted a measurement study on buses using the MONROE mobile broadband testbed [5]. The goal with our measurement experiments is to understand what network performance upcoming C-ITS applications can expect in today's mobile networks, in terms of transaction times and availability. The goal is also to understand if multi-access can help to improve performance and enable new C-ITS applications today. We focus on a simple scenario, common to many C-ITS applications, where a vehicle sends data to a server and receives a reply. For instance, location, destination, speed, or surrounding events (potentially hazardous) are sent to a server, which replies in return with a new route or warnings based on data collected from other sources, such as other vehicles. The time constraint on the transaction varies from tens of milliseconds to seconds depending on the application [1].

In our measurement experiments we triplicate the messages and always perform three transactions in parallel over three different cellular operators. This creates a dataset with which we can compare the three operators in an objective way and with which we can study the potential for multi-access.

In this paper, we study to what degree double-access and triple-access can improve transaction times by always picking the fastest of two or three parallel transactions. We also study to what extent availability can be improved by sending the messages over two or three operators in parallel. Finally, we use the dataset to evaluate single-access selection strategies. In a scenario where there is access to three operators we select one of them for each transaction, based on information about cellular access technology and signal quality.

The rest of the paper is structured as follows: In Section II we describe the MONROE testbed, the measurement set-up and the dataset. In Section III we present the multi-access results. In Section IV we analyse and explain observed variations in transaction times in terms of access technology and signal quality. In Section V we use those insights and

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[1] https://ec.europa.eu/transport/themes/its/c-its_en

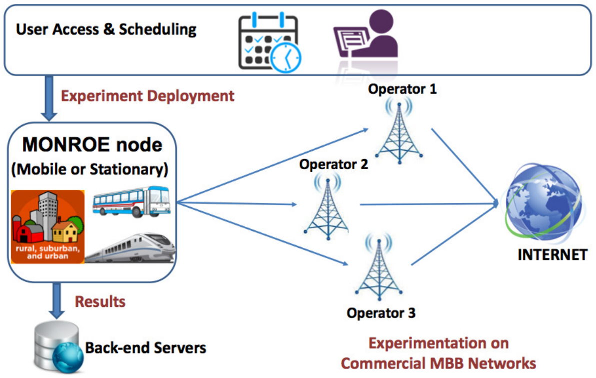

Fig. 1. Key components of the MONROE mobile broadband measurement testbed. Many measurement devices are mobile, deployed on buses, trucks or trains. Each measurement device has access to three operators which enables multi-access experiments.

evaluate two simple single-operator selection strategies using our multi-access dataset. Related work is in Section VI and we conclude the paper in Section VII.

II. MEASUREMENTS

A. The MONROE testbed

For our measurements, we used the MONROE (Measuring Mobile Broadband Networks in Europe) [5], [6] testbed. MONROE is a testbed with hundreds of nodes deployed over Europe. Many of the nodes are mobile on buses, trucks and trains. It is a distributed testbed for measuring, monitoring and assessing the performance of mobile broadband services in an objective manner. The testbed is open to external researchers and provide Experiment-as-a-Service. The measurement devices have access to multiple operators which gives the possibility to compare operators and to perform multi-access experiments. Figure 1 outlines the high-level system design of the testbed: users deploy experiments with a scheduling tool to the measurement devices, each of which are typically equipped with three LTE modems to transmit data over different commercial mobile broadband (MBB) networks. The measurement devices upload results of the experiments into back-end servers, accessible by users for analysis.

B. Experiment design and dataset

We study a scenario where vehicles on the road upload warning messages over cellular networks to a server on the Internet. For this we collected a multi-access dataset using mobile MONROE devices on buses that repeatedly transferred warning messages to a stationary server. We measured transaction time and success rate (availability). For each transaction we also collected meta-data including information about the access technology, signal strength, and GPS position.

To upload a message with a realistic size we formated the warning message with the Datex II XML standard[2], embedding a *situationRecord* element of type *VehicleObstruction*. The total size of the message was 5.6 KB. The server knew what total size of data to expect, and hence replied to the client as soon as all data was received. The reply was an acknowledgement message containing the number of bytes successfully received by the server. In the measurement experiments we used a timeout value of six seconds. If a transaction did not complete within this timeout value we considered the message to be lost and the transaction to be unsuccessful.

In the experiments we triplicated the warning messages and always performed three transactions in parallel over three different cellular operators. The objective was to create a dataset with which we can compare the three operators in an objective way and with which we can study the potential for multi-access.

We ran the experiments on buses operating in both urban and rural areas, in the city of Karlstad and surroundings in Värmland, Sweden. The server was located in Stockholm. The warning messages were transfered using the TCP protocol. During an experiment a new TCP transaction was initiated every 30 seconds. We ran experiments on business days from the morning to early evening. The experiments were conducted between December 2017 and February 2018. The dataset used in this paper includes the results of 4445 TCP transactions, triplicated and run in parallell over three operators. For more details about the experimental design see [7].

III. MULTI-ACCESS RESULTS

Given the multi-access dataset we can study and compare transaction times and availability for each of the three operators. We here refer to the operators as op0, op1, and op2. We can also investigate to what extent availability and transaction times can be improved with double- or triple-access. Since with triple-access we pick the best of three parallel transactions it is obvious that triple-access will perform better than single-access. But it is not obvious beforehand that an improvement will be significant. If one operator is always the best then the benefit with triple-access is limited. If all three operators have poor performance at the same time due to difficult conditions and bad coverage, then the benefit with triple-access is also limited.

Figure 2 shows an example with transaction times during a one-hour experiment with three operators on a bus. The upper graph in Figure 2 shows that the performance of each operator varies and it is not always the same operator that is the best. Triple-access can therefore significantly reduce the peaks in transaction times.

If we take a closer look at the results, in Table I and Figure 3, we see that the median transaction time differs between the three operators: 314ms for op0, 162ms for op1, and 130ms for op2. With double access, where we always can chose the best of two parallel transactions, we get 119ms in the best case and 145ms in the worst case, depending on which two operators we consider. Triple-access gives a median transaction time of 115ms, a decrease of 12% compared to the best single operator and 63% compared to the worst single operator.

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[2] http://www.datex2.eu/

TABLE I

TRANSACTION TIMES (IN SECONDS) AND AVAILABILITY FOR TRIPLE-, DOUBLE-, AND SINGLE-ACCESS.

	Availability	**Min**	**Median**	**Mean**	**90%**	**95%**	**99%**	**Max**	**Std dev**
Single-access op0	97.6%	0.055	0.314	0.410	0.623	1.207	3.504	5.918	0.580
Single-access op1	98.8%	0.092	0.162	0.296	0.425	0.725	2.669	5.983	0.988
Single-access op2	98.7%	0.061	0.130	0.360	0.946	1.167	2.425	5.904	0.537
Double-access (op0,op1)	99.5%	0.055	0.145	0.212	0.344	0.392	1.138	5.983	0.268
Double-access (op0,op2)	99.8%	0.055	0.120	0.198	0.336	0.462	1.042	5.607	0.260
Double-access (op1,op2)	99.8%	0.061	0.119	0.171	0.300	0.377	0.913	5.607	0.235
Triple-access	99.9%	0.055	0.115	0.148	0.245	0.320	0.568	5.607	0.163

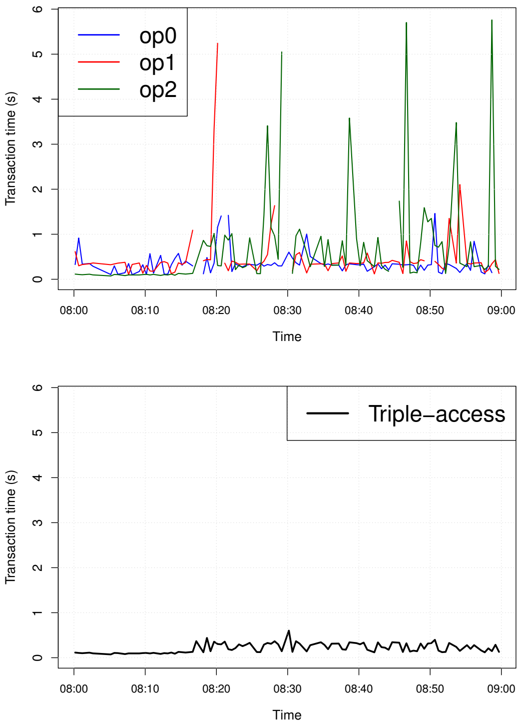

Fig. 2. Transaction times during a one-hour experiment with three operators on a bus. Triple-access, where we always pick the best of three parallel transactions, significantly reduces transaction times.

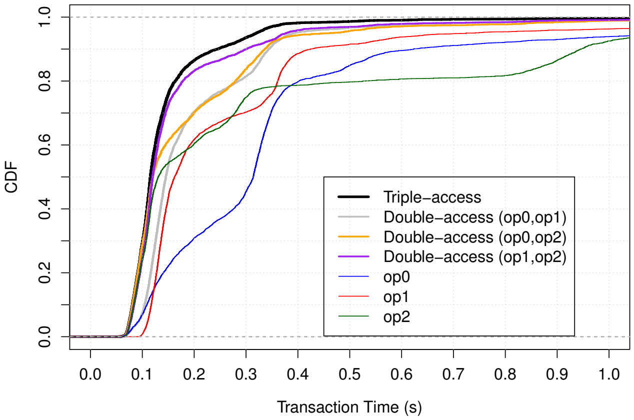

Fig. 3. Transaction times for triple-, double-, and single-access (ECDFs)

The difference between single-, double-, and triple-access is greater if we look at the upper percentiles in Table I. The 99-percentile for the individual operators varies from 2.425 seconds for op2 up to 3.504 seconds for op0. With double-access, the 99-percentile varies between 0.913 and 1.138 seconds depending on which two operators we chose. With triple-access the 99-percentile is reduced further down to 568ms, a decrease of 77% compared to the best single operator and 84% compared to the worst single operator.

The maximum values in Table I are limited by the six seconds timeout used in the experiments, but it highlights that some transactions take more than five seconds to complete.

In our measurements we see large variations in transaction times and it is not always the same operator that is the best. We can conclude that double- and triple-access can significantly improve transaction times and availability when sending messages from moving vehicles.

In the next section we take a closer look at why there are variations in the transaction times. First we study how the transaction times differ depending on access technology (LTE/3G), and then we look at the correlation between transaction time and signal quality.

IV. CORRELATION ANALYSIS

A. Access technology

The transaction time depends on which cellular access technology is available. For a moving vehicle this varies between different locations and between operators. Figure 4 shows comparisons of LTE and 3G transaction times per operator in our measurements in Värmland, Sweden. The median transaction time using LTE was 121ms. The median transaction time using 3G was 339ms. The share of transactions done over LTE differs between operators: op0 18%, op1 66%, op2 60%. If we for instance take a closer look at op2, we see that this operator has a large number of fast LTE transactions, but also a considerable amount of slow 3G transactions. This was also reflected in the cumulative distribution function for op2 that we saw earlier in Figure 3; the median value for op2 was close

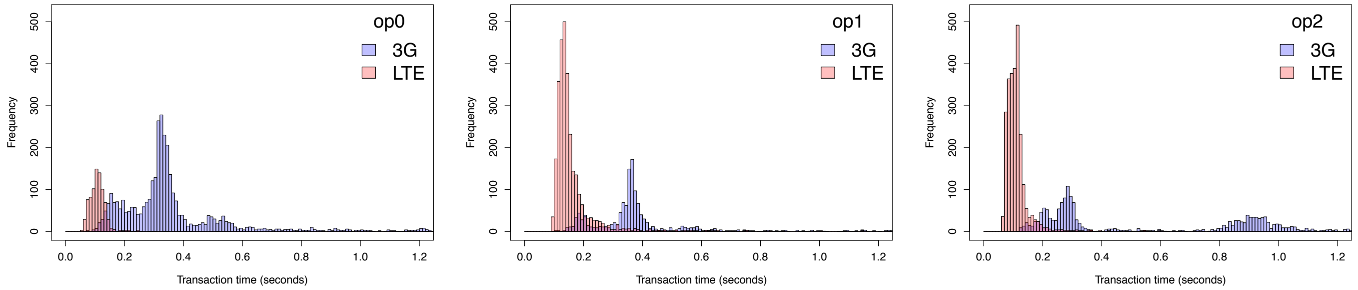

Fig. 4. Transaction times over LTE and 3G for each operator op0, op1 and op2.

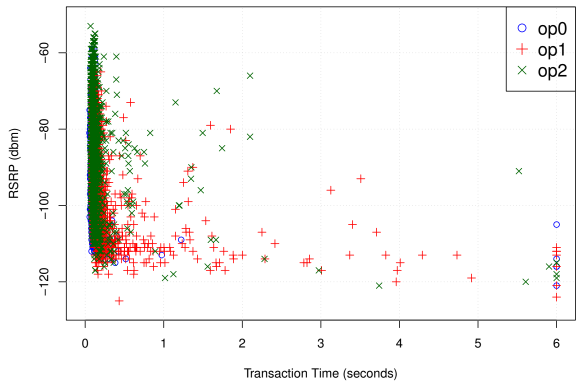

Fig. 5. RSRP plotted against transaction time for transactions over LTE.

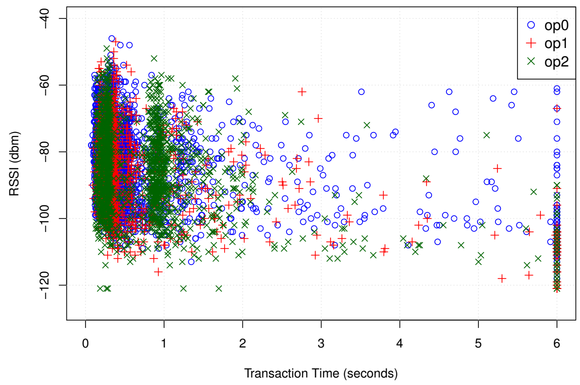

Fig. 6. RSSI plotted against transaction time for transactions over 3G.

to triple-access (130ms versus 115ms) but the 90-percentile for op2 was 946ms compared to 245ms for triple-access.

B. Signal quality

The transaction time may depend on the signal quality. Figure 5 shows a scatter plot with the Reference Signal Received Power (RSRP) plotted against transaction time for TCP transactions over LTE. The time for failed transactions have been set to six seconds. The Pearson correlation coefficient is -0.22. The Spearman's rank correlation coefficient is -0.43. Pearson is the commonly used correlation coefficient. Spearman is rank based and is better suited to non-linear scales, like the log scale in the RSRP data. A correlation coefficient of -0.43 indicates that as the signal strength improves the transaction time decreases, they are negatively correlated. There are no points in the upper right corner of Figure 5, but we see a few points that have both a high RSRP-value and a transaction time above two seconds. There are several points with bad RSRP-value but low transaction time.

Figure 6 shows a scatter plot with Received Signal Strength Indicator (RSSI) plotted against transaction time for TCP transactions over 3G. Here we observe more points in the upper right quadrant, with high RSSI-values and high transaction times. The Pearson correlation coefficient is here -0.32. The Spearman's rank correlation coefficient is -0.23.

TABLE II
TRANSACTION TIMES AND AVAILABILITY FOR SINGLE-ACCESS SELECTION STRATEGIES AND COMPARISON WITH TRIPLE-ACCESS

Strategy	**Avail.**	**Median**	**90%**	**95%**	**99%**
Triple-access	99.9%	0.115	0.245	0.320	0.568
LTE 0-1-2	99.1%	0.134	0.440	0.941	2.247
LTE 1-2-0	99.4%	0.139	0.334	0.504	1.778
LTE 2-0-1	99.2%	0.118	0.356	0.432	1.953
LTE-SQ	99.5%	0.122	0.326	0.518	1.469

V. SINGLE-ACCESS SELECTION

We saw in Section III that having access to multiple operators can substantially improve availability and transaction times compared to having only one operator. But duplicating all transactions over several operators inflicts a data overhead on the cellular network and can be expensive for the end-user. In this section we study what performance we can achieve if we have access to three operators but only use one of them for each transaction.

We use our triple-access dataset to evaluate single-access selection strategies, where one operator is chosen for each transaction based on information about cellular access technology and signal quality. Table II shows the results.

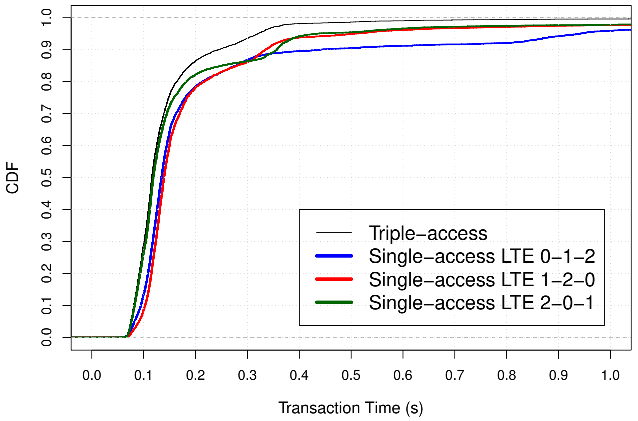

Fig. 7. Transaction times for single-access selection strategies that chose LTE if available. Results for triple-access included for comparison.

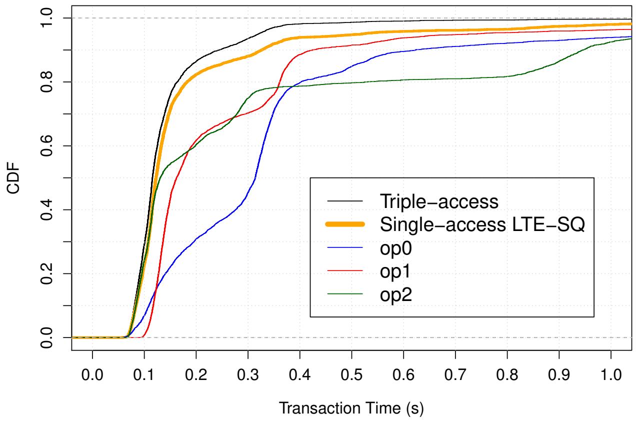

Fig. 8. Transaction times for a single-access selection strategy that choses the best access based on technology (LTE/3G) and signal quality (RSRP/RSSI). Results for triple-access and each individual operator included for comparison.

A. *Selection based on available cellular access technology*

The first strategy is to chose one operator with LTE, if available. Table II and Figure 7 show results for three instances of this strategy. The strategy *LTE 0-1-2* means that for each transaction we prefer op0 if it has LTE, otherwise we choose op1 if it has LTE. If neither op0 nor op1 has LTE then we choose op2 (no matter what access technology it has). There are six distinct operator combinations. Here we present results for three combinations (the other give similar results). The median transaction time with the single-access strategy *LTE 2-0-1* is 118ms. This is close to what can be achieved with triple-access (115ms), but the difference in the higher percentiles are substantial. With the LTE strategies 99.1-99.4% of the transactions succeed, the median transaction time varies between 118-139ms, depending on which operator we have as our first choice, and the 99-percentile transaction time varies between 1778-2247ms. For comparison, with triple-access the availability is 99.9%, the median transaction time is 115ms, the 99-percentile is 568ms.

B. *Selection based on access technology and signal quality*

Figure 8 shows the results for a single-access selection strategy where we in addition to access technology also have information about signal quality. For each transaction we prefer LTE, and if several operators have LTE we choose the one with the best RSRP value; if all operators have 3G we choose the one with the best RSSI value. With this strategy 99.5% of the transactions succeed, the median transaction time is 122ms, and the 99-percentile is 1469ms.

Figure 8 also shows a comparison with each individual operator. We see that, given access to all three operators and basic information about access technology and signal quality, we can improve performance by selecting the best operator for each transaction. The median transaction time improves by 6% compared to the best single operator and by 61% compared to the worst single operator. The 90-percentile transaction time improves with 23% compared to the best single operator and with 65% compared to the worst single operator.

C. *Discussion*

If we for every transaction could predict which one of our three operators that will give the best transaction time, then a single-access strategy would give the same results as triple-access. Information about access technology and signal quality help us to get close to the triple-access results but not all the way. We saw in Section IV that even though there is a correlation between RSRP-values and transaction times, we can obtain good transaction times even with low RSRP values, and there are also examples where we get a bad transaction time even though the RSRP value is good. There are also other factors that sometimes influence the transaction times, including events higher up in the network.

VI. RELATED WORK

Our work is at the crossroads of several areas as it addresses cellular network performance to reduce transaction times. *Vehicular:* one study focuses on the connectivity patterns of vehicles [8]. Khatouni *et al.* [9] measured the downlink performance and RTT for different cellular networks, including in buses, using the MONROE platform [5], [6]. *Multipath:* To reduce latency [10] initiates redundant operations across diverse resources and use the first one to complete, with Multipath being one technique in their work. Multipath are considered by combining cellular and WLAN interfaces in [11]–[15]. All show improvements in latency with differences in their experimental setups. *Cellular only:* Albadejo *et al.* [16] measure the downlink bandwidth and RTT at different fixed locations in Dublin. Huang *et al.* measure the maximum downlink and uplink bandwidth from 20 smartphone users over five months [17]. Sommers *et al.* [18] compare the performance of cellular networks and WiFi networks from a crowd-sourced dataset collected from a speed test application for mobile phones. Xu *et al.* [19] analyse cellular network traces from three different locations and show the predictability of network conditions. *Latency:* A survey on reducing latency in many network types appears in [20]. Works [21]–[23] focus on characterising TCP in HSPDA+ and LTE networks with latency identification and reduction as their focus, [24] on identifying bufferbloat in 3/4G networks. *C-ITS:* Sjöberg *et al.* [25] describe the current status of deployment in Europe. Karagiannis *et al.* [1] survey the main use-cases and applications expected to be deployed with C-ITS. Lu *et al.* [2] survey the different solutions that have been proposed for wireless communication between vehicles.

VII. CONCLUSIONS

We have conducted a multi-access measurement study on buses using the MONROE mobile broadband measurement testbed. We conclude that having access to several operators in parallel can substantially improve communication performance for connected vehicles in today's 3G/LTE cellular networks.

In our measurement experiments, we repeatedly transferred warning messages (5.6KB, Datex II) using the TCP protocol, from moving buses to a stationary server. We triplicated the transactions and sent each warning message in parallel over three operators. The measurement results show large variations in transaction times for each operator, and it is not always the same operator that is the best. Double- or triple-access can therefore considerably reduce the transaction times.

Furthermore, we used the triple-access dataset to evaluate single-access selection strategies, where one operator is chosen for each transaction. We show that if we have access to three operators and for each transaction choose the operator with best access technology and best signal quality then we can significantly improve availability and transaction times compared to the individual operators.

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