A Way to Measure and Analyze Cellular Network Connectivity on the Norwegian Road System

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***Abstract*—The quality of vehicle-to-vehicle and vehicle-to-infrastructure communication is a highly relevant aspect for the successful adoption of Intelligent Transportation Systems. In this paper, we present our plans to collect connectivity-related data on the Norwegian road network on a big scale. For that, a fleet of transporters will be equipped with Android devices sensing relevant connectivity data like the signal strength of cellular networks or the round trip delay of messages sent from a device to a remote server and back via these networks. The retrieved data are then stored together with the GPS data of the location where the measurements were taken. Data collected at the same place during various tours are aggregated, and the resulting data set can be used for various kinds of analysis and prediction. We introduce the architecture of our Android-application. Moreover, we discuss the results of some first experiments taken during various tours in a sparsely populated area around Trondheim. In particular, we found out some interesting correlations between the signal strength and the round trip delay which are quite different depending on the communication protocols used.**

I. Introduction

Vehicular mesh networks and cellular networks are seen as the two main technologies to enable vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communication [1]. Currently, cellular networks are used for V2I communication that is not very real time and safety critical while the direct communication between vehicles with low latency demands is realized by connecting them directly using mesh technology. A big step in the progress of mobile networks will be the next generation, the so-called 5G technology. Due to its better quality of service provision, 5G can handle and disseminate more data in a shorter time and with a greater reliability such that cellular networks will also be suited for real time-critical connectivity [2].

Nevertheless, already the current generation of 3G and 4G cellular networks allows the application of a plethora of Intelligent Transportation Systems (ITS) that need less stringent requirements of dissemination delays and errors. Examples are information services for, e.g., fault prediction, data collection and dissemination, efficiency improvement, and convenience that are all seen as an important part of vehicular systems [1]. Moreover, mobile networks can be exploited to disseminate and distribute rich information and large amounts of data to the cloud (see, e.g., [3]). Also the use of hybrid communication systems is a highly relevant research and development topic for academia, governments, automotive companies, and other interested parties. Hybrid networks will combine different mesh and cellular networks making a more efficient usage of the available bandwidth possible [4].

Both technologies can only work sufficiently if they guarantee a data exchange that is persistent, reliable, and scalable to a large number of vehicles in the area [1], [5]. Achieving these quality of service properties can be challenging in countries like Norway which is quite elongated and, in parts, very sparsely populated. The low vehicle density in some areas makes the practical use of mesh networks difficult since there are not enough vehicles within the network transmitter range [5].

For cellular networks, coverage, mobility, and capacity as well as the available channels and transport modes are seen as important concerns for the practical use in V2V and V2I [6]. For instance, mobile and WiFi networks are often arranged to primarily serve inhabited areas but not the roads in between, particularly, when these are minor [7]. Furthermore, mountainous terrain that is prevalent in many parts of Norway, can aggravate the reachability and quality of cellular networks [8]. Mountains and hills can cause echoes of signals that are often received with a significant delay [9].

To get a general idea of the cellular network coverage on their road system, the ITS group of the Norwegian Public Road Administration (NPRA) started recently a collaboration with the NTNU ITS Lab. in Trondheim. NPRA disposes of a fleet of light lorries that constantly ride on the road network to make measurements of all kinds. These cars will be provided with Android devices that run an application sensing relevant connectivity parameters like the current signal strength or round trip delay at a certain location. The interval between two recordings can be parameterized. In the moment, a measurement will be taken every second such, depending on the speed of the car, the roads are gauged in distances of up to 30 meters. The sensed values taken at a location during various trips can then be stored, aggregated, and examined. In this way, we can make various statistical analyses for both, the country in general and particular road segments that are of importance.

In a first step, we will analyze the three mobile phone networks operated by Telenor, Telia, and Ice.net. Later, similar measurements will also be taken for other network types like WiFi and Digital Audio Broadcasting which in the form DAB+ is the main radio standard used in the country. The aggregation of all this information will make it easier for the NPRA to decide which ITS services can be suitably realized in Norway and which network technology should be used. In addition, the data may help to suggest the cellular network operators useful places to improve the connectivity as well as to decide about convenient places to install roadside units (see [10]).

In Sect. II, we introduce the parameters that will be sensed during our field tests. Thereafter, we describe the mobile Android-based application in Sect. III and the tool used to aggregate the data in Sect. IV. In Sect. V some first experimental results will be discussed followed by a look on related work and a conclusion.

II. Parameters of Interest

As mentioned above, our main interest in this project is to find out information about the connectivity of cellular networks at various locations. The *signal strength* of a mobile network can be used to characterize the quality of a connection. In mobile devices, the signal strength indicator (RSSI) [11] describes the radio power with which the device receives messages [12]. In Android, one can apply the RSSI value or, alternatively, the Arbitrary Strength Unit (ASU) which expresses the signal strength by integer values between 0 and 31 (resp. 99, showing that the signal strength could not be determined). Here, 0 refers to no signal reception at all while 31 describes the reception of the transmitted signals without loss. In our location-depending measurements, we use the current ASU value as a parameter.

A second value relevant for the quality of a connection is the *round trip delay*, i.e., the time interval between sending a message and receiving its confirmation. It is a relatively easy way to estimate the network latency [12] which, in contrast, to separate measurements of uplink and downlink connections does not rely on perfectly synchronized computer clocks. To determine the round trip delay, our device sends at each measurement a data packet containing the time stamp at the transmission to a server at NTNU. The server replies immediately with a packet containing the received time stamp, and the device compares this time stamp with the one taken when receiving the reply. The difference is the round trip delay that is measured in milliseconds and added to the location measurement data as a parameter.

Another parameter is the communication protocol connecting the device at a location. In the measurements up to now, that were limited to Telenor's network, we detected three different protocols: EDGE, HSUPA, and HSPA+. The Enhanced Data Rates for GSM Evolution (EDGE) [13] is a bridging technology bringing 2G GSM networks to the 3G standard. The two other protocols are members of the High Speed Packet Access (HSPA) family [14]. The High Speed Uplink Protocol Access (HSUPA) and its counterpart, the High Speed Downlink Protocol Access (HSDPA), are native 3G protocols offering higher data speeds than EDGE. Evolved High Speed Packet Access (HSPA+) improves the maximum uplink data rate of $5.76 Mbit/s$ provided by HSUPA to $22 Mbit/s$ and the maximum downlink rate of $14 Mbit/s$ offered by HSDPA to $42.2 Mbit/s$. Due to the improved data speeds, it is used to upgrade 3G networks to 4G technology. Thus, it is another bridging technology.

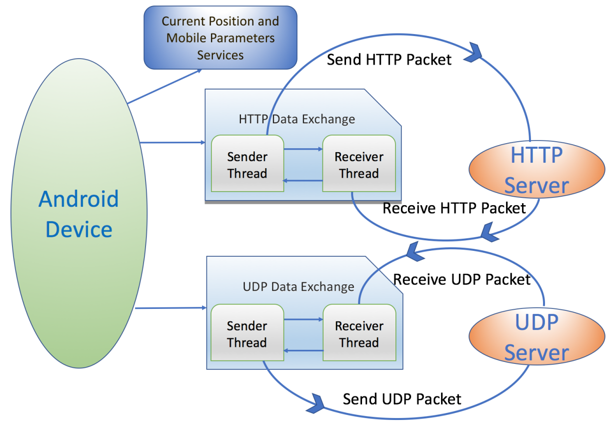

Fig. 1. Architecture of the Android application.

Finally, we added various parameters about the Global Positioning System (GPS) used to identify the exact location of a device. Besides the *latitude* and *longitude* as measurements for the location, we store the *altitude* as well as the *bearing* and *speed* of the device. Further, to get more information about the quality of GPS measurements, we sense the *accuracy* of the location determination as well as the total number of GPS satellites in reach and the one used for identifying the location.

III. A Mobile Android Application

Our tool needs to retrieve all the parameters mentioned in Sect. II in an effective and reliable way. Moreover, it shall be customizable in order to adapt it fast to new tasks if necessary. Nowadays, there is already a myriad of applications, that can be used to analyse the network performance, available for Android and IOS devices. A drawback of these applications, however, is that they are not open-source such that it is hardly possible to customize them. To overcome this obstacle, we have developed an own Android application that can be installed in various types of Android devices.

The architecture of this application is shown in Fig. 1. Android Java has a built-in set of methods that are used to collect information about the state of network connectivity, e.g., the current signal strength, which are part of the class *ConnectivityManager*. To retrieve the GPS-related data, we use the Google Play services location API [15]. Amongst other things, this API makes it possible to request the last known location of the user's device.

For the communication with the server to compute the round trip delay, we support both, UDP and HTTP. In both cases, the transmission of packets which takes place every second, is separated from the reception of the packets confirmed by the server. This separation is achieved by using different threads managing the sending resp. receiving of packets. The collected data is saved in the local memory of the Android device. Usually, the dimension of the data is quite moderate. On a test trip of around 17 hours, we produced a data set of a length of 7,737 Kilobytes. Since our devices have a memory of at least 32 Gigabytes, we can therefore store data recorded over more than eight years, in theory. We think about an automatic transmission of the retrieved data to our server but refrained from that for the moment since we want to find out first if such data exchanges can falsify our connectivity measurements.

At NTNU in Trondheim, we installed an HTTP server as well as a software sending UDP packets back. Both, programs are built using the model-based software engineering technique Reactive Blocks [16], [17] (see Sect. IV). The sole task of both programs is to reply on incoming messages as fast as possible in order to allow for precise round trip delay measurements.

IV. Location-based Aggregation

Like for the server used to immediately reply to round trip delay messages, we developed an aggregation tool using Reactive Blocks. This software development technique makes it possible to define reusable sub-functionality in special building blocks that are combined to a system model from which executable code is automatically generated. The building blocks can be easily adapted and exchanged which gives us the necessary flexibility to adjust the data aggregation to our particular needs.

In its current state, the tool allows us to group connectivity data to geographical cells of a parameterizable size. Usually, we use rectangular geographical cells with a side length of 20 meters. The Android application generates a database containing an entry for each of the geographical cells. Currently, a database entry comprises the number of measurements made at locations within the geographical cell, the communication protocols through which the device was connected, and the location of the cell, i.e., its latitude and longitude measured by GPS. Moreover, the minimum, maximum, average, and variance is added for both, round trip delay and signal strength measurements. The generated database can be used for statistical analysis and visualization of relevant facts in geographic information systems as we will show in the following.

V. Some First Experimental Results

To test our Android tool-set with the mobile network offered by Telenor, we made some short distance car trips to the Jonsvatnet lake outside of Trondheim (see Fig. 2). This area is probably the closest one to the city that has spots in which the cellular network coverage is low. Altogether, we visited the area three times in June, August, and October 2017 driving around the lake clockwise. During the August tour, we could surround the lake twice and once during the other trips. At the October tour, we had to take another way back to the city due to a road closure.

Figure 2 shows an excerpt of a freely available topographical raster map taken from Geonorge [18]. We use the geographic information system QGIS [19] to show the results of our measurements on the map. The measured values were aggregated to geographical cells of a size of 20 meters, and each dot in our figures represents to a single cell. The colored

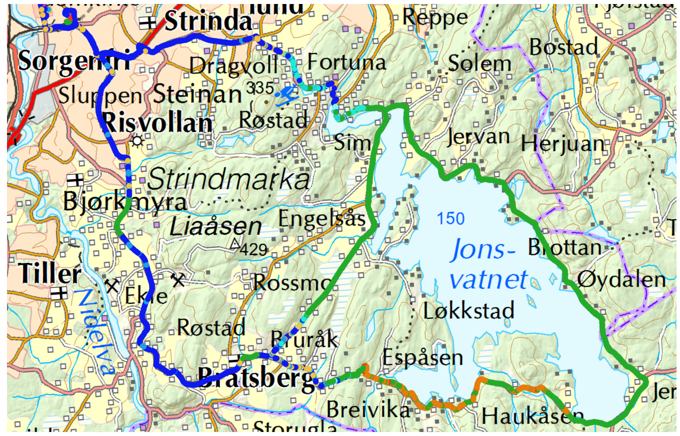

Fig. 2. Protocol coverage in the Jonsvatnet lake area.

Fig. 3. Average and variance of the measured signal strengths.

line in Fig. 2 refers to the cellular communication protocols used at the three tours (see Sect. II). Not surprisingly, in the areas closer to the city center, which is in the Northwest of the map, our device was mostly linked using the HSPA+ protocol as shown by the dark blue color of the line. In contrast, in the rural areas around the lake, the connection was based on EDGE. This is illustrated by the green color. On a short leg around Fortuna, the device was connected using HSUPA as shown in light blue.

Of interest is the orange line south of the Jonsvatnet lake between Haukåsen and Breivika. It describes that for some measurements, EDGE was used while during other ones, the device could not connect at all. A look on the data produced during the different tours revealed that the device lost the connection more often at the one in June than during the other two trips. Thus, it seems that Telenor has in between improved the network access in this area. Altogether, there were only nine 20 meter cells in this area (presented in red) in which the device was never connected. The remaining colors refer to cells in which various protocols were used in different measurements. Such cells are mostly at the borders between the areas using HSPA+ resp. EDGE.

The signal strength measured in the Jonsvatnet area is shown

Fig. 4. Average as well as minimum and maximum values of the measured round trip delays.

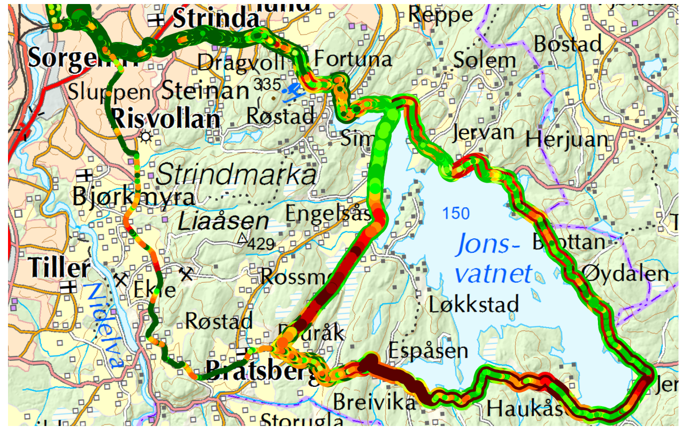

Fig. 5. Averages of the measured round trip delays during the three trips.

in Fig. 3. The figure contains two bands. In the inner one, we depict the averages of the signal strengths measured in the 20 meter cells. As discussed in Sect. II, Android allows us to express the signal strengths in form of ASU values between 0 and 31 that are depicted by a color gradient reaching from red via yellow to green. Signal strength values between 0 and 6 are shown in reddish colors, between 6 and 12 in orange, between 12 and 18 in yellow, between 18 and 24 in light green, and between 25 and 31 in dark green. Interestingly, there are very few areas with averages shown in dark green, not surprisingly mostly in the city center. On the other side, there are not that many areas with low values either, mostly on the south side of the lake. The relatively bad values measured between Bratsberg and Tiller on the single trip done in October came as a surprise to us since that is basically a populated area. A reason might be that HSPA+ seems to apply tighter standards with respect to signal strength measurements than EDGE. The average of signal strengths measured for HSPA+ is, in general, lower than that for EDGE.

The variance of the signal strengths measured in a cell is shown in the outer band. Here, we also use a color gradient between red, yellow, and green where green refers to a low and red to a high variance. Mostly, the variance is relatively low, and we measured similar signal strengths on the three trips. An exception is the area around Haukåsen but that likely results from the network improvements discussed above.

Our round trip delay measurements based on HTTP for the communication between the device and the server at NTNU are depicted in Fig. 4. Here, we show the averages measured in the cells in the inner band, the minimum value of each cell in the middle band, and the maximum value in the outer one. The color schemes of all three bands are equal: Short round trip delays until up to a second are shown in greenish colors, delays until three seconds in shades between green and yellow, round trip delays until 20 seconds in orange, and even longer delays in red. The figure reveals that in the HSPA+ network, the round trip delay is quite steady and mostly below 250 milliseconds as shown by the dark green stripes. Interestingly, that also holds for the area between Bratsberg and Tiller where we measured low signal strengths. In contrast, the situation in the areas in which our device was connected via EDGE is less clear. On the northwestern part of the lake around Sim, the delays were also relatively steady with values between 750 milliseconds and two seconds as shown by the light green colors. But in various areas around the lake, the round trip delay has a high variance. There, the minimum values were also in the range of less than two seconds while the maximum values were mostly above a minute as depicted by the line in burgundy.

To get to the bottom of this effect, we look on the round trip delay averages for the three trips in separation. The outer band in Fig. 5 refers to the tour in June, the middle one to the trip in August, and the inner band to the one in October. While the round trip delays in the HSPA+ cells are quite similar and mostly under a second, there was a clear lack in the areas supported by EDGE on our tour taken in August. The round trip delays on the east, south, and west side of Jonsvatnet are quite similar in June and October and mostly below two seconds. In contrast, at the trip in August, the averages are here very bad and often longer than 20 seconds, and that holds for both surroundings of Jonsvatnet done during that tour.

Currently, we have no proper explanation for this effect. All three trips were taken at working days. The June tour was done antemeridian, the August trip around noon, and the October tour in the later afternoon during rush hour. While we cannot interpret these wildly varying round trip delays in the areas connected via EDGE based on our current data, we are confident that the data to be collected in the future may be of help. A sufficiently large data set should make it possible to analyze the above mentioned observations more deeply. Maybe, we can find certain patterns for that, e.g., the dependence on the time of the day, which will be helpful to decide about the practical usability of ITS technology.

Finally, we like to discuss the relation between the signal strength and the average round trip delay for both, EDGE and HSPA+ networks considering all the aggregated data points of our testing trips around Jonsvatnet. The functions mapping the

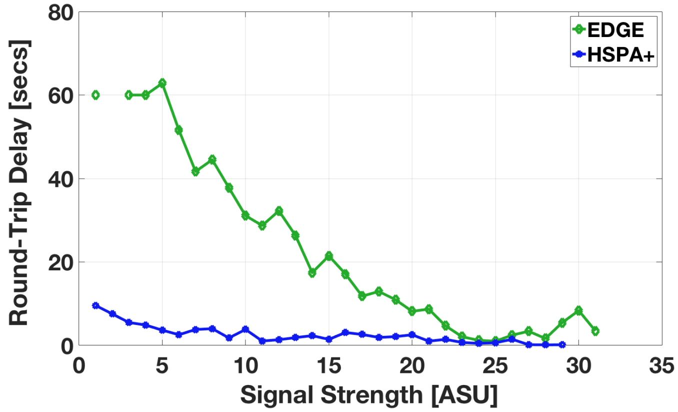

Fig. 6. Round trip delay distribution as a function of the signal strength for EDGE- and HSPA+-based networks.

rounded ASU values describing the average signal strengths in the various geographical cells to the mean round trip delays based on HTTP is presented for both protocols in Fig. 6. To assess the round trip delay in function of signal strength for the HSPA+ network, we have considered in total 1102 data points. The signal strengths of almost 80% of these points were between 1 and 20 in the ASU metrics (see Sect. II) and there were no points in our trips with an aggregated signal strength of 30 or 31. As might be seen in the figure, the round-trip delay very slightly improves as the signal strength increases, but the overall performance of the system is very stable. Even though, our cellular network is HSPA+, this result corresponds with the one presented in [12] for a network using Long-Term Evolution (LTE), a full 4G protocol.

Our analysis also reveals that in the EDGE network protocol, the signal strength has a much greater impact on the round-trip delay of the packets, as can also be seen in Fig. 6. The function shows a clear trend for a strong correlation between the signal strength and the round-trip delay when the device is connected via this protocol. To assess the curve for the EDGE network, we considered 1481 data points. Almost 80% of them have an ASU value between 12 and 24. Of course, we have to validate this trend by using greater data sets[1].

In addition, we found out for both network technologies that switches between the protocol types have a big impact on the round-trip delay. In areas of the road, where the network technology is stable and the signal strength is not very poor, the round-trip delay for both protocol types is less than 1000 milliseconds. Not surprisingly, the performance of HSPA+ is in such areas much better than the one in EDGE networks.

VI. Related Work

To our best knowledge, we are the first planning to conduct network access data for the most significant roads of a whole country with the goal to gain a general view of the network connectivity on various locations. Nevertheless, there already exists some work making network quality measurements at certain locations to find out about the possibility to launch certain ITS services. For instance, Promnoi et al. [20] have built a database of the signal strength measured at various places in Bangkok, Thailand. The signal strength matching allows them to calculate the number of mobile phones in a certain area and to estimate the road traffic based on that. Like us, the authors make their measurements in intervals of one second. Similarly, Gundlegård and Karlsson [21] measure the signalling quality of UMTS networks in Sweden in order to find about traffic density and to calculate optimal ways for vehicles to guarantee a short travelling time. Inam et al. [12] use the geographical position of vehicles to identify the quality of line video streaming using cellular networks in order to make the remote operation of the vehicles possible. They conduct their tests in Kista in Sweden.

Other approaches use location-based measuring to plan the improvement of the cellular network infrastructure. Quite early, Nakano et al. [22] suggested the use of spatial data to plan the design of cellular networks. Puspitorini et al. [10] use measurements at various locations in Surabaya, Indonesia, to decide about suitable locations for establishing road side units.

Connectivity parameters at certain places were conducted also for WiFi and Mesh networks. Bychkovsky et al. [23] tested various connectivity parameters of open IEEE 802.11-based WiFi networks in Boston and Seattle to find out about the usability of these networks for vehicular access. Similar analyses were made by Mahajan et al. [24] at the Microsoft Campus in Redmond, WA. In contrast, Cheng et al. [25] used vehicle locations to estimate the connectivity of vehicles via Dedicated Short Range Communication (DSRC)-based Mesh networks. They made their tests in suburban areas of Pittsburgh, PA. A scalable way to collect and use sets of vehicular data in a cloud to, amongst others, exchange the locations of vehicles, is offered in the Cloudthink platform proposed by Wilhelm et al. [3].

Finally, we like to refer to the work of Mecklenbräuker et al. [7] who give a very good overview about various types of connectivity issues at different network types. In particular, their distinction of network issues for varying infrastructures like highways, city centers, suburbs, and rural roads, is highly useful for our work.

VII. Conclusion and Future Work

We presented a relatively inexpensive approach to collect data describing the connectivity of cellular networks at certain locations, e.g., signal strength and round trip delays. Devices running our application will retrieve data on various parts of the Norwegian road system using NPRA's fleet of lorries.

The data will be of high relevance in various respects. As already mentioned, they will help NPRA to get a general knowledge about the cellular network coverage on their roads. Thus, it gets much easier to decide about which ITS technology can already be reliably applied using the current state of the cellular networks. Further, the data ease the prediction

[1]For instance, the peak at value 30 in the function for EDGE is based on the fact that there was only a single cell with this value in average, and there we had a relatively long average round trip delay of around eight seconds.

which changes of a network will be necessary to make a technology practically usable and how expensive that will be. In particular, NPRA can determine at which locations the network has to be improved resp. supporting road side infrastructure needs to be installed to make a certain ITS technology operational.

Our first tests in the Jonsvatnet lake area showed that the collected data may also be helpful to find out more about the general usability of cellular networks for ITS. As is known, the networks were not primarily developed and deployed for the use of ITS applications. Thus, one needs a deep understanding of the potential and limitations of the networks for which the collected data may be very helpful.

The tests discussed in Sect. V inspired a first extension of the Android application. We suppose that changes between cells have a significant impact for the round trip delay. As written in Sect. V, that holds, particularly, if such a switch comes along with a change of the communication protocol used. To be better able to analyze our data for this presumed effect, we are changing the Android application such that it also records the number of the cell through which the device is connected. We will also analyze how the lengths of the transmitted packets as well as the transmission period influence the quality of the system performance. Moreover, we plan to use machine learning techniques to make the analysis of patterns in our data easier.

In addition, we plan to use the connectivity data to improve the routing in hybrid networks that contain both, cellular and mesh technology. Here, the data may help a vehicle that is temporarily not connected to decide based on its current location how to forward messages. Let us assume that a vehicle surrounds Jonsvatnet in a clockwise direction. In the weak connectivity spot between Haukåsen and Breivika, an ITS application in the vehicle detects ice on the road that it likes to report to a stationary server as fast as possible. However, this transmission is inhibited due to a missing connection. If the vehicle is still in Haukåsen and in reach of another vehicle in the opposite direction, it may be best to pass the message to the other vehicle since that reaches an area with good connectivity shortly from which it can forward the message. If our vehicle, however, is already in Breivika, it is probably better to wait the short time until it reaches an area with better connectivity from where it can send the message itself. A first prototypical application of such a location-aware routing algorithm shall be developed in a master's thesis at NTNU in Spring 2018.

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