Measuring and Modeling Aggregate LTE Connection Reliability for Train Operations

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***Abstract*—We examine the connection reliability of LTE cellular infrastructure for supporting train signaling systems. In particular, the impact of simultaneous use of multiple networks on reliability is considered, along with failure correlation effects. We present a tailored reliability model, and report on data collected from many train-mounted cellular routers. Connection reliability reaches 99.994% when aggregation is used, compared to 99.953% for the best single link. Both modeling and measurement results show greatly improved reliability when aggregating over multiple links, thus indicating that commercial cellular networks may be useful for providing connectivity to future train signaling system.**

***Index Terms*—cellular networks, connection reliability, train control**

I. INTRODUCTION

There are today over 20 different national signaling and speed control systems in the European rail system which creates an obstacle to the free flow of rail traffic across Europe. Hence, the main purpose of the European Rail Traffic Management System (ERTMS) is to replace these old and mutually incompatible legacy train protection and safety systems with one pan-European system. At the heart of the ERTMS system is the signaling and control component named European Train Control System (ETCS) [1]. To carry the ETCS signalling, ERTMS uses a GSM system (GSM-R), dedicated for railway communication. GSM-R utilizes its own infrastructure and radio spectrum but is expected to be replaced by 5G around the year 2029 and then renamed Future Railway Mobile Communication System (FRMCS) [1]. The combination of FRMCS and 5G will be key enablers for Automatic Train Operations (ATO), thus reducing transport emissions and contributing to make rail a more competitive transport alternative while improving customer experience.

However, the full cost of deploying ERTMS/FRMCS along the tracks throughout the complete European railway network is estimated at between 73 and 177 Billion Euros [2]. At the same time, other regions outside of Europe are also implementing train control systems based on wireless communication. The Positive Train Control system (PTC) [3] is a less advanced system mainly designed for train protection and safety, and has since 2008 been deployed all over the United States. The total cost for developing, purchasing, installing, and maintaining PTC has been estimated to be up to $22 Billion [4]. All these critical train control and signalling systems depend on highly reliable connectivity, with sufficient capacity and appropriate delay characteristics.

In parallel to the evolution of critical rail control, there has been a rapid development of techniques and systems to provide reliable and high-capacity internet access to passengers onboard the train, as well as to non-critical aspects of train operations such as data collection from sensors for predictive maintenance, onboard point-of-sale equipment, etc. Such on-board internet access systems often use external train-mounted cellular antennas connected to an onboard router that aggregates several concurrent cellular connections on multiple operator networks [5]. Today such systems, aggregating both 4G and 5G, may provide a peak capacity to the train greater than one gigabit per second. Such router-based solutions with multi-operator connectivity by necessity provides additional capacity, greater coverage and higher reliability compared to what any single-operator cellular wireless infrastructure would be able to provide (cellular or dedicated radio network) [5]. Furthermore, router-based solutions can also be technology and operator independent, supporting multiple technologies and operators. In many deployment contexts this can be a major advantage compared to using any type of relay node, or repeater, which would typically be both technology- and operator-dependent.

This work provides the following contributions: 1) a reliability model that captures the essential characteristics of a cellular train communications system, 2) a large-scale empirical characterization of train reliability, and 3) a quantification of connectivity failure correlation and the associated impact on reliability.

The remainder of this paper is structured as follows. The next section provides further background and discussions of related work, followed by a section detailing the proposed reliability model. Results from a study on large scale empirical data is then provided from multiple perspectives, followed by the conclusions.

II. BACKGROUND AND RELATED WORK

There are multiple studies that provide an overview of wireless networks for rail communication. In [6] the key technologies in 5G are reviewed, and a network architecture with separate train mounted relays are proposed for passenger and rail control traffic. On the network side, different network slices would target the passenger and railway-dedicated services. The survey in [7] discuss LTE and 5G for train control, and also reviews additional supporting techniques such as WiFi and Radio-over-Fiber. In [8] a LTE test network is evaluated for train control over a 12km test track which includes a long tunnel and a bridge. The results indicate that LTE is capable of upholding the required quality for unmanned operation, but the tested network was using several tweaked RRC timers, and the QoS was evaluated against the specific Korean KRTCS.

Work on train control and traffic management which explicitly considers multi-path solutions include [9] which proposes the use of multi-path TCP (MPTCP) together with multiple operators, and satellite communications in coverage holes where there is no cellular connectivity. A subflow management algorithm is proposed, and evaluated in an emulated environment. The same approach was also evaluated in an 300 km railway section with a maximum train speed of 150 km/h and using rooftop antennas and Inmarsat BGAN satellite [10]. In [10] a cost assessment was also provided, highlighting the potential savings. Similarly, in [11] MPTCP is proposed as a mechanism to increase redundancy. The approach is further evaluated in [12] where integrating MPTCP over heterogeneous radio bearers to the ERTMS stack is examined, aiming to achieve seamless fail recovery similar to the EIRENE requirements that guides GSM-R design. Their reported results, based on simulations, indicate that the performance is well in line with the EIRENE requirements.

There are also relevant work which is not considering train control, and one such work [13] reports on an ambitious measurements study performed onboard High-speed trains in China. Like many other train measurement studies not focusing on train control applications, this study measures the cellular conditions as experienced by mobile devices inside the train carriages. Since the train carriages heavily attenuate radio signals unless special consideration have been taken when constructing the trains, such measurement studies do not reflect the radio conditions that would be expected for a train control application, where external antennas would be used. The study reports that over the 7820 kms covered in 68 journeys, the probability of both operators performing handover at the same time is nearly zero. The median number of handoffs per minute is 3, and 4, for the two examined operators.

From the regulatory perspective, the European union agency for railways considers 5G as the preferred technology for the Future Railway Mobile Communication System (FRMCS) [14]. In [1] the strategic deployment agenda of the organizations for European Infrastructure Managers (EIM) and Community of European Railway and Infrastructure Companies (CER) is outlined. The report highlights the essential need of 5G in order to allow both improved operational effectiveness through ATO and higher ERTMS levels, as well as for providing high-capacity internet access to train passengers. The report also highlights the economic gains when sharing both passive 5G infrastructure such as towers, power supplies, fiber backhauls, as well as potentially active network elements (i.e. 5G slicing). Other work also argue for why 5G would be the judicious choice for the railway domain [15]. An overview of potential railway communication technologies and technology building block such as MPTCP is discussed in the X2Rail-1 deliverable [16].

III. CONNECTION RELIABILITY MODELLING

We are interested in studying the effects of using multiple concurrent cellular links to improve the overall connectivity of the train. It is well known from reliability engineering that parallel redundant subsystems increase the system reliability. If one models the $n = 4$ links employed by the router as four parallel subsystems, and apply the conventional reliability engineering formulation for parallel systems [17] the resulting system connection reliability $E[R_P]$ is expressed as :

$$E[R_P] = 1 - \prod_{i=1}^{n} [1 - E[R_i]] \tag{1}$$

where $E[R_i]$ is the reliability of the i:th of the n parallel subsystems. However, while this formulation illustrates the large increase in system reliability provided by using multiple parallel systems, it has some assumptions that are not necessarily applicable in the context of cellular connectivity onboard trains. The modelling approach inherited from reliability engineering assumes that the connectivity failures are independent between the subsystems (i.e. links). This is not the case when two links are connecting to the same cellular operator. Additionally, the connection reliability of any link is not constant as assumed in (1), but is dependent of the geographical location the train is present in, which in turn changes as the train moves. Geographical features such as tunnels may induce connectivity failures which are correlated across operators. Furthermore, time effects also come into play as the connection reliability for some geographical location may not be the same over time due to changes in the cellular infrastructure. There may also be spurious local events that affect the cellular network for shorter time periods.

To address these modelling issues, we here provide an initial sketch of a more suitable connection reliability model. The model is composed of the following subparts:

- $R_I(l, o, m)$ models the infrastructure reliability. This subpart captures the coverage of a particular operator o at some geographical location l at some time moment m. The main parameters are l and o as the infrastructure state is mostly stable over time, with some infrequent step changes occurring such as when a new cell site is established.
- $R_E(l, o, m)$ models spurious events that affect the cellular communication conditions. Such events are occurring at

some limited location as indicated by l, and exist for some limited time period as given by m. The spurious event may be operator independent, i.e. affecting all operators to a similar degree and thus independent of the o parameter. The event can alternatively be operator-specific in that the event only affects one operator o, or it may be some middle-ground between these two cases.

- $R_V(v, d, m)$ models connection reliability aspects that are specific to the particular train individual v. The types of antennas mounted, or the types of cellular modems used, may vary between trains and result in different connection reliability for different trains in the same location and time-span. Different aspects of train-specific reliability can be constant over time, or coupled to time if for example the modem types are upgraded at some time moment. Some aspects may further affect only a specific link d as for example if a modem breaks down, or the quota coupled to that specific subscription is exhausted.
- R_R is the residual which models variation in reliability not addressed by any of the above subparts.

We note that the time parameter m here identifies time epochs between relatively rare discrete state changes in infrastructure, events, and vehicles. Continuously varying random time phenomena are here represented in R_R. All the above model subparts need to be simultaneously viable in order for connectivity to be present, thus forming a serial dependence between working infrastructure, no adverse events, and working vehicle conditions.

With this more elaborate model we can now express the aggregate connection reliability of individual observations R_O at location l along the rail track at time moment m for operator o, train vehicle v and link d as

$$
\begin{aligned}
R_O(l, o, m, v, d) = 1- \quad & (1 - (\max_d (R_I(l, O(d), m) && (2)\\
& \qquad\qquad R_E(l, O(d), m) && (3)\\
& \qquad\qquad R_V(v, d, m))) && (4)\\
& R_R) && (5)
\end{aligned}
$$

where $O(d)$ is a function that maps link d to its corresponding operator o. Connectivity is coded as $R_S = 1$ and non-connectivity as $R_S = 0$ and $R_I, R_E, R_V, R_R \in [0, 1]$ The parallelism of the multiple links is expressed by the maximization expression in (2), which signifies that as long as at least one link has connectivity then the system has connectivity. Since the maximization extends over (2) to (4), the serial dependence discussed earlier is modeled so that the subparts need to simultaneously be viable for connectivity to be present. This formulation clearly highlights that connection reliability is composed of several subparts which can be modeled and evaluated separately. The per observation model can then be extended to a system reliability model by considering the connectivity correlation between operators, which can be estimated based on empirical data. As we are here mainly interested in improving our understanding of link aggregation on system reliability we in this study focus on the R_I and R_E model subparts.

IV. EMPIRICAL RELIABILITY RESULTS

A. *Description of the Data Set*

To perform the analysis we utilize a data set collected by trains equipped with onboard routers that provide Internet access to train passengers. The routers are connected to roof-mounted external antennas and have four modems that are connected to two or three different mobile operators. Every five seconds the routers record the current position as determined by GPS, train velocity, connectivity status and a range of cellular metrics. We analyze the 615 km long train line between Malmö and Stockholm, and consider data collected between January 2019 and March 2021. In this period 50 different train sets, predominantly X2000 high-speed trains, performed 12049 journeys where each journey lasted on average 4.5 hours.

For each modem the system keeps track of the current connectivity status with the metric `gw`. This metric indicates whether or not a certain link is connected to the packet gateway used for the aggregation of the connectivity links, with a 15 second timeout.

B. *Connection reliability over time*

Due to the richness of the dataset, the analysis can be performed from many different viewpoints, and with varying granularity. We initially consider the connection reliability of the individual links in comparison to the case where link aggregation is used, and examine how this reliability evolves over time. As the analysis is over time, it relates to all model subparts that have a m parameter. Here, we consider data from the 730 journeys performed by the train which most frequently operated on the studied train line. Figure 1 shows the average per journey connectivity fraction, for each of the four links, along with the connectivity when link aggregation is employed. The results in the upper graph show that there is significant difference between the operators, where operator 1 consistently have lower average journey reliability. This difference between the operators is consistent with previous measurements of operator differences in Sweden such as [18], which report availability figures of 97.3% and 98.6% for two different Swedish operators. Also, in [19] around 10 dBm difference in median RSRP between the operators is reported, when measured using antennas mounted on train roofs. It should be noted that the modem for link 1 (yellow) had a change of SIM-card at 2020-09-03, so after that date the link 1 values are for Operator 3. The other links have SIM-cards for the same operators (1 and 2) assigned throughout the whole time period, so in the further analysis we focus on these links.

In order to better view the results in the region of most interest, i.e. the high reliability region, this region is displayed in the lower subfigure in Figure 1. As can be seen the average per journey reliability for operator two is quite high, with an average of above 0.999 for a majority of one-week bins. The results for aggregated connectivity is as expected superior, and

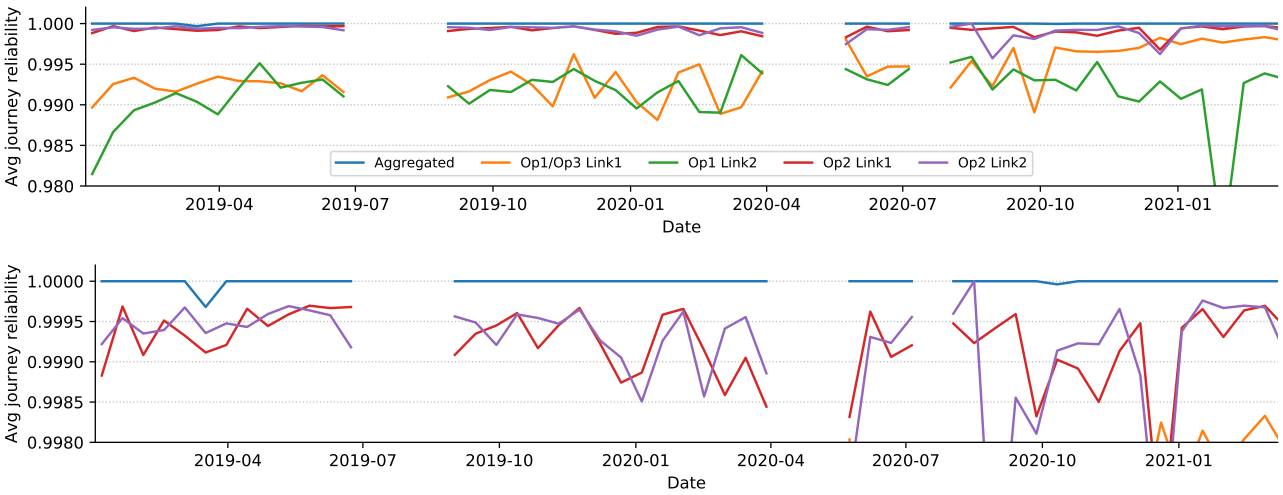

Fig. 1. (Top) Average fraction of Malmö - Stockholm journey observations which reported connectivity metric `gw` as true, over time, for the most frequent train individual. Per journey averages are averaged over one week periods, and shown for each of the four individual links, and for the aggregate where connectivity is considered present if at least one link per observation is True. (Bottom) Same as upper but with zoomed in y-axis.

shows a reliability of 1.0, in terms of the `gw` metric, for the vast majority of journeys. For this train close to 2.4 million observations were collected per link. Out of these observations, the fraction which had connectivity was 99.5915%, 99.9732% and 99.8067% for operators 1, 2, and 3, respectively, and 99.9986% when using link aggregation. The breaks in the graphs correspond to time periods when the analyzed train individual was not running on the considered train line, and thus no data was generated.

C. *Connection reliability over location*

As the train travels along the track radio coverage conditions will differ, and the connection reliability will thus also vary. In a location-bound analysis, the model subparts that have an l parameter are relevant. As the single train data examined above does not have sufficient number of non-connectivity observations to study geographical dependencies, we now consider data from the 10 most frequent trains. When studying location-bound connectivity a suitable metric is needed, as average journey connectivity is not appropriate. Instead, we here consider one kilometer segments of the train line, and examine the connectivity each time a train passes through a given segment. We define *segment reliability* to be 1 when all observations in one such a passing has connectivity, and 0 when at least one observation in the passing does not have connectivity. As such, the segment reliability metric is more aggressive since a single non-connection observation will have a proportionally larger impact on the metric. The number of observations per segment varies, as it is coupled to the speed with which the train passes through the segment, and also if the train stops at a station within a segment. For the 3.2 million passings, across the 615 segments, the average number of observations per passing is 5.3.

The connectivity over the train line is shown in Figure 2 with the aggregated case in the topmost subfigure, and for link 2 of each of two operators below. Note the difference in y-axis scales. Again, the results vividly illustrate the effectiveness of aggregation, as well as a marked difference between the two operators. The horizontal banding that can be discerned in the top graph occurs simply because the number of passings with any non-connectivity is so small. From the top, the bands below 1.0 correspond to one, two, three, etc passings with at least one observation of non-connectivity in any observation, out of the 5188 passings that occur per bin. For this data subset with 10 trains, close to 16.9 million observations were collected per link. Out of these observations, the fraction which had connectivity was 99.5870%, 99.9531% and 99.3302% for operators 1, 2, and 3, respectively, and 99.9936% when using link aggregation. To determine the positions along the track, the GPS readings were used. While these are accurate for the vast majority of observations, they are likely to be unreliable when the train passes through a tunnel, and this may impact the allocation into the corresponding bins. While this may impact some individual bins, we do not expect this to have any impact on the overall conclusions. We intend to study mitigation approaches to improper GPS positioning as part of future work.

D. *Impact of correlation on reliability*

To explore the effect of correlation on system reliability we compute the empirical correlation for the same data as used in Fig. 1, i.e. from a single train. To simplify, we only consider data from 2020-10 onwards since this period consistently had three operators used over the four links. We compute the phi coefficient, which is equivalent to the Pearson correlation coefficient when computed for binary variables. In addition to the `gw` metric discussed earlier we also explore two alternate metrics relating to connectivity. The first such metric focuses on radio conditions and considers the Received Signal Reference Power (RSRP). Here, RSRP > -115 dBm is used

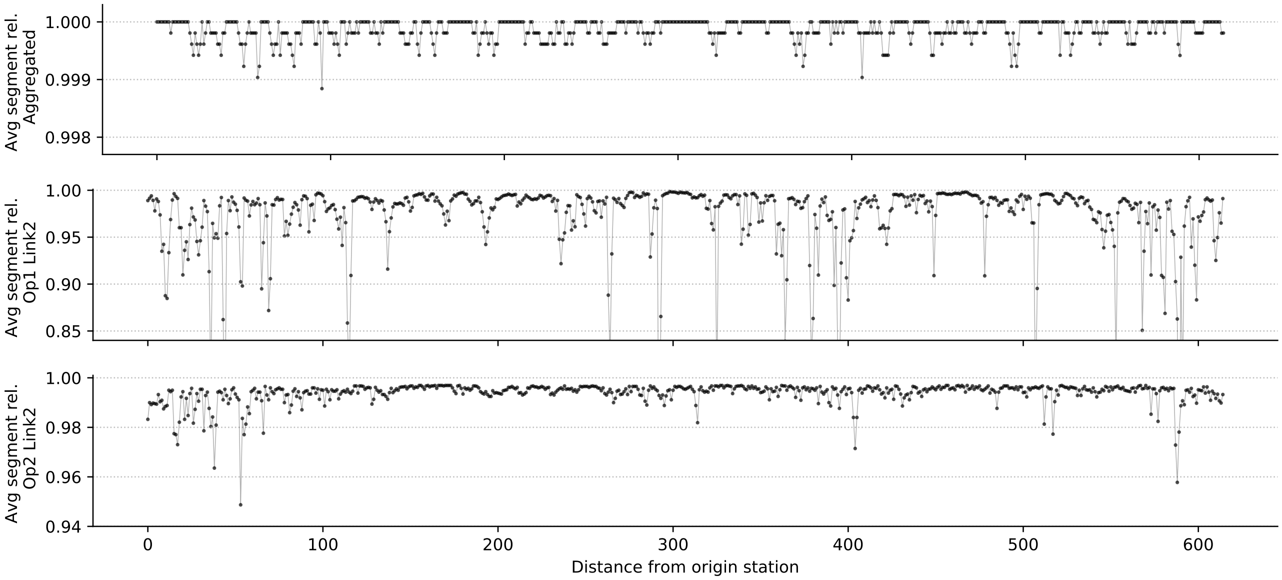

Fig. 2. Fraction of all journeys which reported connectivity metric `gw` as true for all observations within each 1-km stretch of the rail line, computed for the 10 trains with most journeys. The top graph shows the results when considering aggregation over four links, i.e. at least on of four links reported true for all observations when the train passed the stretch. The middle graph shows link 2 of operator 1 and the bottom graph shows link 2 of operator 2. Note the different scales on the y-axes.

to represent a minimal radio level connectivity. The second metric considers higher communications layers, and examines the number of received bytes reported by the link interface. As small amounts of control traffic is continuously sent, a number of bytes should always be received when connectivity is present.

Reliability and correlation values for the three metrics are shown in Table I. All three metrics in general show similar tendencies in terms of reliability and correlation which suggests a degree of robustness in the evaluation approach. For all metrics, operator 2 has the best reliability $E[R_i]$ as would be expected given the results shown in Fig. 1. The correlation coefficient ρ ranges between 0.002 to 0.15, with the correlation values for the `gw` metric being noticeably lower than for the other two metrics. We hypothesize that this is related to the 15s timeout which is applied internally in the router for the `gw` metric. Such timeout is not present for the other metrics.

TABLE I
RELIABILITY AND CORRELATION COEFFICIENTS FOR DIFFERENT CONNECTIVITY METRICS OVER THE FOUR LINKS

	Op3	Op1	Op2Link1	Op2Link2
`gw` connectivity metric				
Reliability, $E[R_i]$	0.99891	0.99567	0.99973	0.99977
Correl: Op3	1.0000	0.0103	0.0087	0.0096
Correl: Op1	0.0103	1.0000	0.0020	0.0041
Correl: Op2Link1	0.0087	0.0020	1.0000	0.0337
Correl: Op2Link2	0.0096	0.0041	0.0337	1.0000
Link RSRP > -115 dBm				
Reliability, $E[R_i]$	0.99732	0.99286	0.99974	0.99974
Correl: Op3	1.0000	0.0706	0.0319	0.0318
Correl: Op1	0.0706	1.0000	0.0188	0.0187
Correl: Op2Link1	0.0319	0.0188	1.0000	0.1516
Correl: Op2Link2	0.0318	0.0187	0.1516	1.0000
Recieved bytes on link > 250				
Reliability, $E[R_i]$	0.99728	0.99326	0.99900	0.99858
Correl: Op3	1.0000	0.0758	0.0659	0.0567
Correl: Op1	0.0758	1.0000	0.0326	0.0276
Correl: Op2Link1	0.0659	0.0326	1.0000	0.1249
Correl: Op2Link2	0.0567	0.0276	0.1249	1.0000

We can also analytically examine how varying degrees of correlation affects the resulting system reliability $E[R_P^{Cor}]$. As shown in [20], when the link reliability, $\mu = E[R_{link}]$, and correlation, ρ, is assumed to be identical for all four links,

$$E[R_P^{Cor}] = \frac{1-\left(1-\mu\left(1+\rho\frac{1-\mu}{\mu}\right)\right)^4}{1+\rho\frac{1-\mu}{\mu}}. \qquad (6)$$

While this assumption is not strictly supported by the empirical results as observed in the table, this simplified formula allows the relationship between correlation and reliability to be straightforwardly visualized for the value range of interest. The resulting analytical reliability expressed as $\overline{E[R_p]} = 1-E[R_p]$ is shown in Fig. 3. We note that the expected reliability as computed by the basic parallel subsystem formula in (1), i.e. the curve for $\rho = 0$, severely misstates the reliability when correlation is present. Conversely, fully correlated subsystems ($\rho = 1$) degenerates to the same performance as a single

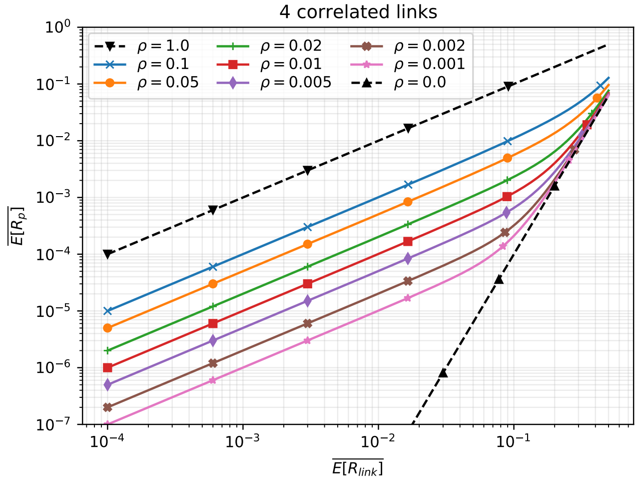

Fig. 3. Resulting system reliability for some link reliability $E[R_i]$ and link correlation ρ, when $E[R_i]$ and ρ are identical for all four links.

subsystem/link as all systems then always fail concurrently. Between these extremes lines, correlation values relevant to the empirically observed range are provided. We note the considerable difference in empirical correlation between the intra-operator and inter-operator case present in Table I. If all links would connect to a single operator correlation would increase, resulting in order-of-magnitude reduction of reliability as shown in Figure 3.

V. CONCLUSIONS AND DISCUSSION

This study has evaluated connection reliability along a rail line in Sweden when considering link aggregation over four links connecting to two or three cellular operators. The results show a considerable improvement in both coverage and reliability with a mean connectivity fraction of 99.994% with link aggregation. This can be compared to 99.953% when considering only a single link of the best performing operator. By proposing a dedicated reliability model, we facilitate the reasoning around reliability variation over time and space, and lay the ground for exploring the impact of link failure correlation.

Considering the huge investment necessary for deploying and operating a dedicated and fully redundant 5G network for rail, exploiting already existing commercial infrastructure offers a great opportunity to reduce the overall cost for society. By applying link aggregation (as examined here) and using virtualized network infrastructures in the form of 5G slices, existing commercial mobile network infrastructure may provide part of the underlying connectivity or redundancy. This will reduce the need of dedicated infrastructure hardware and the associated costs. In principle such a deployment strategy could be applied to most critical infrastructure, e.g. networks for Public Protection and Disaster Relief (PPDR), resulting in higher network reliability, better coverage and lower investment cost for taxpayers.

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