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High Reliability in Wireless Networks Through Multi-Connectivity

David Öhmann

von der Fakultät Elektrotechnik und Informationstechnik der
Technischen Universität Dresden
zur Erlangung des akademischen Grades eines

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Vodafone Chair Mobile Communications Systems
Institut für Nachrichtentechnik
Fakultät Elektrotechnik und Informationstechnik
Technische Universität Dresden
01062 Dresden, Germany

Abstract

While today's mobile networks are mainly used for connecting people, upcoming fifth generation (5G) technologies have the potential to expand wireless communication into a broad range of new applications and industries, with nearly everything being connected. Important parts of this vision are *Ultra-Reliable Low-Latency Communication* (URLLC) and the *Tactile Internet*, which enable controlling objects in real-time but also require unprecedented high reliability and low latency.

This thesis lays theoretical foundations for understanding and enhancing the reliability and availability of wireless networks. The primary approach followed is to model the statistical behavior of relevant components and to develop (semi-)analytical tools for in-depth analysis of small outage probabilities. Initially, availability and survivability models are introduced for different combining schemes and small-scale fading channels. It is shown that, for achieving a particular availability, utilizing multiple low-power links can be considerably more power-efficient than using only a few powerful links. Moreover, novel closed-form expressions of the Minimum Duration Outage are derived for multiple selection-combined Rayleigh fading links.

The core contribution of this thesis is a signal-to-interference-plus-noise ratio (SINR) model that captures shadowing as a random component but considers a realistic user association based on total receive powers including shadowing. The SINR model enables a fast yet accurate analysis of the availability performance of wireless networks. Various system properties, e.g., multiple path loss models and antenna types, are considered for traditional sub-6 GHz carrier frequencies and higher frequencies in cmWave and mmWave bands. Results demonstrate that interference-limited sub-6 GHz carrier frequencies are, in principle, better suited to achieve the goals of URLLC, especially when interference mitigation techniques are applied in addition. Nonetheless, the availability of noise-limited higher carrier frequencies can be enhanced as well, for instance, by adapting the power spectral density. Moreover, intra- and inter-frequency multi-connectivity prove to be promising concepts for increasing the availability of wireless networks to a level suited for URLLC and Tactile Internet applications. Furthermore,

the SINR model is combined with other causes of failure, namely mobility issues, non-radio failures, and small-scale fading, to a unifying framework for joint system analysis. The extension by mobility aspects provides valuable insights into how mobility deteriorates the availability performance and reveals that intra- and inter-frequency multi-connectivity have the potential to compensate for mobility effects.

Kurzfassung

Ultra-Reliable Low-Latency Communication (URLLC) und das *Taktile Internet* ermöglichen es, Objekte in Echtzeit über Funkverbindungen fernzusteuern, und haben das Potenzial, eine Vielzahl neuartiger Anwendungsfelder und Märkte für Mobilfunktechnologien zu erschließen. Allerdings ist es dafür erforderlich, eine bislang in der Funkkommunikation nicht erreichte extrem hohe Zuverlässigkeit und niedrige Latenzzeiten zu garantieren.

Die vorliegende Arbeit liefert theoretische Erkenntnisse, die das Verständnis fördern und Möglichkeiten zur Steigerung der Zuverlässigkeit und Verfügbarkeit von Mobilfunknetzen aufzeigen. Der hauptsächlich verfolgte Ansatz ist, das statistische Verhalten von relevanten Komponenten zu modellieren und darauf aufbauend (semi-)analytische Methoden zu entwickeln, die es ermöglichen, kleine Ausfallwahrscheinlichkeiten mit hoher Genauigkeit, jedoch geringem Aufwand zu ermitteln. Zu Beginn werden Verfügbarkeitsmodelle für verschiedene Combining-Verfahren und Fadingkanäle eingeführt. Die Anwendung der Modelle zeigt, dass eine gewünschte Verfügbarkeit in bestimmten Fällen mit deutlich geringeren Gesamtleistungen erreicht werden kann, wenn viele leistungsschwache anstatt weniger leistungsstarker Übertragungen genutzt werden. Des Weiteren wird ein theoretisches Modell für Selection Combining und Rayleigh-Fading entwickelt, welches sehr kurze Ausfallzeiten der Funkkanäle toleriert und realitätsnähere Untersuchungen ermöglicht.

Der Hauptbeitrag dieser Arbeit ist ein Modell des Signal-zu-Interferenz-und-Rausch-Verhältnisses (englische Abkürzung *SINR*). Dieses Modell behandelt Abschattungseffekte (engl. *shadowing*) als Zufallsprozesse und berücksichtigt eine Wahl der Zielzelle basierend auf Gesamtempfangsleistungen inklusive der Abschattungseffekte. Das SINR-Modell zeichnet sich dadurch aus, dass es schnelle und dennoch genaue Analysen von Verfügbarkeiten von Funknetzen ermöglicht. Zudem können wichtige Systemparameter und -charakteristiken wie z.B. mehrere Pfadverlustmodelle und Antennentypen in das Modell integriert und dadurch sowohl klassische Mobilfunkfrequenzen unterhalb von 6 GHz als auch zunehmend genutzte Frequenzen im Zentimeter- und Millimeter-Frequenzbereich betrachtet werden. Die Anwendung des Modells zeigt auf,

dass die interferenzlimitierten Frequenzen unterhalb von 6 GHz besser zur Erreichung der Ziele von URLLC geeignet sind – insbesondere, wenn zusätzlich Techniken zur Vermeidung von Interferenz angewendet werden. Allerdings kann auch die Verfügbarkeit bei rauschlimitierten höheren Funkfrequenzen gesteigert werden, indem z.B. die spektrale Leistungsdichte erhöht wird. Außerdem zeigt sich, dass Intra- und Inter-Frequenz Multi-Konnektivität (engl. *intra- and inter-frequency multi-connectivity*) vielversprechende Verfahren zur Erhöhung der Verfügbarkeit und Erreichung der von URLLC und dem Taktilen Internet gesteckten Ziele sind. Darüber hinaus wird in dieser Arbeit das SINR-Modell mit anderen Fehlerursachen wie z.B. nicht-funkbedingten Systemausfällen und durch Mobilität verursachten Störungen kombiniert und zu einem Gesamtmodell erweitert. Insbesondere die Mobilitätsuntersuchungen liefern wichtige Erkenntnisse, wie Mobilität die Verfügbarkeit von Übertragungen beeinflussen kann. Zur Vermeidung von durch Mobilität bedingten Störungen und zur Realisierung von Hochverfügbarkeit bewähren sich wiederum die genannten Multi-Konnektivitäts-Verfahren.

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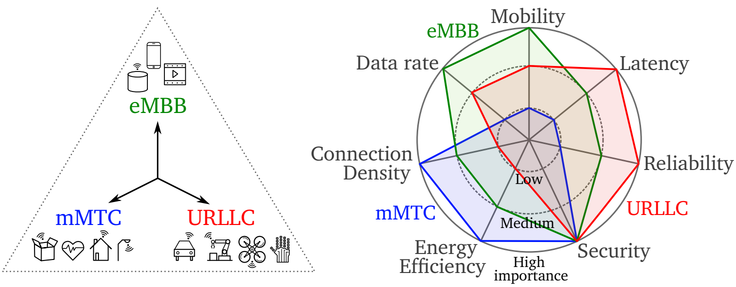
Contents

1 Introduction

1.1 Motivation and Background

Wireless communication has become an integral part of modern culture. Nowadays, it is mostly taken for granted to access and share information everywhere and at all times. In order to support the ever increasing data demand and improve the efficiency of data transmissions, mobile networks have been continuously improved and upgraded. Currently, the fifth generation (5G) of mobile networks, which additionally addresses radically new types of applications, is being envisioned, designed, and standardized.

Academia, industry, and standardization groups have agreed on three main application categories to be supported by 5G networks [NGMN15; Mal16; IR15]. The three categories and corresponding application requirements are depicted in Fig. 1.1. First, enhanced Mobile Broadband (eMBB) focuses on traditional services provided by mobile networks, namely data as well as voice communication. The primary goals in this regard are capacity and data rate enhancements with peak data rates greater than 10 Gbit/s. The second application category is massive Machine Type Communication (mMTC), with an enormous number of devices being connected to the network, e.g., to monitor the environment. Exemplary use cases are smart home, smart city, and smart logistics [Sha+15; Rat+15]. Here, the key metrics are the number of supported devices and the battery life of the connected sensors. Third, Ultra-Reliable Low-Latency Communication (URLLC), also called critical MTC, addresses unprecedented use cases



(a) Application categories in 5G. **(b)** Requirements.

Fig. 1.1. Main categories and requirements of upcoming 5G applications (based on [IR15; MET16a]).

where objects are controlled and steered remotely in real time [Nok16]. An important driver behind this development is the Tactile Internet, which manifested the idea of real-time wireless control [Fet14; IT14].[1] Exemplary applications of URLLC are cooperative automated driving [Hob+15], industrial automation [Fro+14], and remote surgery [Eri16].

Ultra-Reliable Low-Latency Communication

This thesis focuses on the challenging requirements of URLLC, which demands high reliability of 99.999% or greater in combination with low latency in the order of milliseconds. Moreover, high availability is an essential prerequisite for URLLC.

Unfortunately, the basic availability of today's mobile networks is insufficient for URLLC. For example, in the last months, all three German mobile networks experienced serious network failures lasting several hours, e.g., Telekom (database errors on June 12, 2016 [RPO16]), Vodafone (server errors on March 10, 2016 [HO16]), and O_2 (power outage in data center on November 21, 2015 [MT15]). The report in [Spi16] corroborates that network outages happen frequently. On average, a mobile operator experiences 5.7 network outages or severe service degradations per year, which, in addition to unsatisfied customers, occasions monetary costs of approximately $20 billion worldwide per year [Spi16].

In addition, guaranteeing high reliability, which means that a certain amount of data is transferred with high probability in a given period of time [3GP16d], is a most widely unaddressed topic so far. Although new Quality of Service Class Identifiers (QCIs) have been recently added to the 3rd Generation Partnership Project (3GPP) Long Term Evolution (LTE) standard, the latter is still unsuited for the challenging requirements of URLLC [3GP14b]. The additional QCI 70 is supposed to address mission-critical data communication with a packet error rate (PER) of 10^{-6}; however, the maximum delay budget is specified as 200 ms, which is far too long for supporting URLLC. In summary, current communication infrastructure and existing communication protocols are inappropriate to satisfy the stringent requirements of URLLC. New concepts, algorithms, and system architectures are needed to meet those strict requirements.

The main technique for providing reliability and availability is adding redundancy, which is an established principle in many other disciplines as well. Examples are redundant power supplies of information technology (IT) infrastructure and multiple instances of flight control systems in aircraft, see [Gou11; Yeh96]. However, additional redundancy may also increase the complexity of the system

[1] Please note that the Tactile Internet is not limited to mission-critical applications but also includes low-latency applications in other areas, such as edutainment and gaming.

causing other unexpected failures [Dow09]. Redundancy in wireless communication channels is referred to as diversity, which can be used in several dimensions and forms. Common diversity types are frequency, time, polarization, and space diversity [TV05]. Users can be connected via multiple carrier frequencies, at different times, via several antennas, and to a number of base stations (BSs). System architectures where users are connected via multiple communication links are also referred to as multi-connectivity (MC) [MVD16]. However, although different types of diversity have been extensively studied in literature, it is unclear how much diversity and what kind of system architecture are required to meet the requirements of URLLC. Furthermore, a common problem is how to analyze systems that experience only small outage probability, as it is the case for URLLC. Utilizing standard system simulations may be cumbersome or even infeasible due to high computational complexity. One way out, which is also pursued in this thesis, are modeling approaches, which enable an accurate system analysis while keeping the computational complexity low.

1.2 Outline

The reliability and availability of mobile networks are harmed by various causes of failure. This thesis focuses on the wireless downlink channel and the most important radio propagation phenomena such as small-scale fading, large-scale fading, and path loss. Related aspects such as inter-cell interference and mobility management are investigated as well. The core idea and methodology of this thesis is to statistically characterize the different components of the wireless channel and develop models that serve as tools to identify and understand the reliability and availability of mobile networks. Furthermore, based on the models, parameter trade-offs are shown, and different system architectures are compared. Equally important, various carrier frequencies, including upcoming centimeter wave (cmWave) [Mog+14] and millimeter wave (mmWave) [Rap+14] frequencies, are evaluated regarding their capability to support URLLC. The results provide valuable insights for designing 5G networks.
The remainder of this thesis is structured as follows.

- In Chapter 2, basic definitions of important terms, potential causes of failure, and relevant use cases are introduced. Furthermore, the current state of research on reliability, availability, latency, and MC is presented. Based on this overview, the limitations of prior art and the corresponding contributions of this thesis are explained.

- In Chapter 3, small-scale fading is discussed as a potential cause of failure. For doing this, the statistical properties are presented, and the optimal number of links for achieving high availability with a given total power is analyzed. Another important aspect is the duration of outages, which is investigated by a derivation of the Minimum Duration Outage (MDO).
- Thereafter, large-scale propagation and interference are considered as causes of failure in Chapter 4. A model for the signal-to-interference-plus-noise ratio (SINR) is derived and various system architectures, e.g., single-connectivity and MC schemes, are evaluated.
- Then, in Chapter 5, another cause of failure, namely mobility issues, is integrated into the SINR model from Chapter 4, and the impact of mobility on the availability performance is analyzed.
- In Chapter 6, multiple causes of failure are incorporated into a single evaluation framework to facilitate a joint analysis. Furthermore, trade-offs between rate, bandwidth, latency, and reliability are presented, followed by a discussion of different joint coding and combining schemes for inter-frequency MC.
- Finally, the thesis is concluded in Chapter 7.

For illustration, the essential parts and topics of this thesis are visualized in Fig. 1.2.

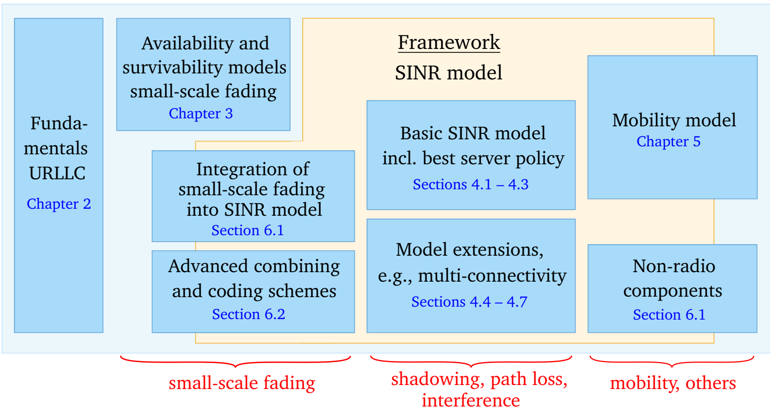


Fig. 1.2. Overview of the main parts of this thesis.

High Reliability in Wireless Networks

2

In this chapter, general definitions and relevant use cases of URLLC are introduced. Moreover, potential causes of failure in mobile networks are discussed, followed by a presentation of the current state of research on high reliability, high availability, and low latency.

2.1 Definitions

Reliability and related terminology have been used in various areas and different contexts; thus, commonly accepted definitions exist. These general definitions are given first, and, then, the specific terminology is explained that is used in the domain of wireless communication.

2.1.1 General Definitions

First of all, different types of problems are specified. According to definitions from software engineering in [IEE90; HP11], the terms *fault*, *error*, and *failure* are distinguished. A *fault* refers to an "incorrect step or definition in a computer program" and represents a *latent error* [IEE90]. If the faulty component is used, an *effective error* occurs, which, in turn, may lead to a *failure*, meaning that the current system state deviates from the expected state. To summarize, faults cause errors, which can result in failures.

In a maintained system, where failures appear and repairs are made, up- and downtimes occur. Up- and downtimes can be specified by the interconnected terms *reliability*, *survivability*, and *availability* as given below, according to [MM06; RH08; Sil+12].

Reliability describes the probability that a system that is in an operative state will perform the required function for a specified period [IT07]; hence, reliability characterizes the uptimes of a system. Assuming that the time to failure is denoted by t_f with the cumulative distribution function (CDF) F_{t_f}, the reliability $R(t)$ is given, as in [RH08], by[1]

$$R(t) = \mathbb{P}\left[t_\mathrm{f} > t\right] = 1 - F_{t_\mathrm{f}}(t) \quad \text{for } t > 0. \tag{2.1}$$

[1] Throughout the thesis, probability density functions (PDFs) and CDFs are denoted by $f_{(\cdot)}$ and $F_{(\cdot)}$, respectively.

Thus, $R(t)$ represents the probability that the system does not fail until time t. Another related common metric is the mean time to failure (MTTF) capturing the average time it takes for the next failure event. According to [RH08], it is expressed as

$$\mathrm{MTTF} = \mathbb{E}\left[t_\mathrm{f}\right] = \int_0^\infty t \cdot f_{t_\mathrm{f}}(t)\,\mathrm{d}t. \tag{2.2}$$

Survivability specifies the process of recovering from a failure and, hence, describes the downtime of a system. A typical metric is the mean time to repair (MTTR) circumstantiating the average time the system needs to return to an operative state. Furthermore, survivability is related to the term *resilience*, which commonly qualifies the capability of a system to continue operation in case of failures [And85].

Availability is the probability that a system is operational and combines information about the up- and downtimes of a system. The availability A is obtained by

$$A = \frac{\text{uptime}}{\text{uptime} + \text{downtime}} = \frac{\mathrm{MTTF}}{\mathrm{MTTF} + \mathrm{MTTR}} = \frac{\mathrm{MTTF}}{\mathrm{MTBF}}, \tag{2.3}$$

where the mean time between failures (MTBF) describes the average time between two failures, i.e., $\mathrm{MTBF} = \mathrm{MTTF} + \mathrm{MTTR}$. More mathematical details can be found in [RH08].

2.1.2 Definitions Used in Wireless Communication

In the area of wireless communication, the most common interpretation of reliability, which is also used in recent publications, e.g., [MET16b; Pop14; NGMN15], is as follows. **Reliability characterizes the probability that a certain amount of data is successfully transferred from the source to the destination within a specified period of time** [3GP16d]. Here, the term reliability is not exactly used according to its general definition since the initial state of the system is irrelevant. The only objective is to accomplish a given task by the end of a deadline.

In addition, several usages and interpretations of availability exist. Firstly, availability is sometimes used to delineate the probability that a reliable service is present [Sch+14; 3GP16b]. Secondly, availability can also embody the fraction of an area for which a certain quality of experience or a reliable service is provided [MET16b]. Thirdly, availability frequently quantifies the fraction of time for which the network and IT infrastructure is operational [Spi16].

In this work, **availability describes the probability that connectivity of a particular quality is provided**. The quality can be characterized by different metrics, e.g., signal power, SINR, or data rate. If a relevant metric z is above a predefined threshold Z, the system is regarded as available, i.e.,

$$A_z = \mathbb{P}[z > Z] = 1 - F_z(Z). \tag{2.4}$$

The reliability and availability of a wireless connection are closely related. Under certain conditions, it is also possible to connect reliability and availability in a simple way. If the system status, especially the wireless channel, does not change during a period that is longer than the time constraint associated to reliability, a certain availability level can directly describe the reliability performance. An example is as follows. An application requires to transfer 1000 bits from the source to the destination within 1 ms. If the system status (including the wireless channel) remains constant, and no other dynamic actions are involved, the connection needs to provide a minimum rate of 1000 bit/ms ($\triangleq 1$ Mbit/s). Hence, the availability measure that the system achieves this particular rate also describes the reliability performance.
Since URLLC applications have very stringent latency requirements, it is likely that the communication channel remains approximately constant during the available transmission time. For this reason, the reliability requirements of URLLC applications can also be expressed as availability requirements, and most of the models presented in this work focus on the availability performance of wireless networks.

In Tab. 2.1, exemplary availability levels and corresponding statistics are shown. In combination with a time constraint, similar levels can be defined for reliability as well. There are different ways to express and label availability. It can be given in percentage, e.g., 99.999%. Other representations are the number of nines, e.g., five nines, or the probability of outage, e.g., 10^{-5}. The latter is computed by $1 - A_z$. In the third and fourth columns of the table, the outage probability is given as fractions of time and space, respectively. Here, a year and a soccer field are taken as reference values. To give an example, an availability of five nines means that only five minutes per year or the area of a sheet of paper per soccer field are allowed to be in outage. Naturally, the higher the desired availability, the tougher it is to fulfill the requirements.

Furthermore, the definitions of **soft and hard real-time requirements** are worth mentioning [KAH07]. In real-time systems, the utility of a message does not only depend on the content of the message but also on the time of delivery. In a system with soft real-time requirements, a delayed completion of a task

Tab. 2.1. Levels of availability.

Availability A_z	Outage Probability $(1-A_z)$	Time: Downtime per Year	Space*: Area in outage as a fraction of a soccer field
90% ("one nine")	10^{-1}	36.5 d	714 m^2 (≈ penalty area)
99.0% ("two nines")	10^{-2}	3.65 d	71.4 m^2
99.9% ("three nines")	10^{-3}	8.76 h	7.14 m^2
99.99% ("four nines")	10^{-4}	52.6 min	0.714 m^2
99.999% ("five nines")	10^{-5}	5.26 min	714 cm^2 (≈ DIN A4)
99.9999% ("six nines")	10^{-6}	31.5 s	71.4 cm^2 (≈ 5€ note)
99.99999% ("seven nines")	10^{-7}	3.15 s	7.14 cm^2 (≈ stamp)
99.999999% ("eight nines")	10^{-8}	315 ms	71.4 mm^2
99.9999999% ("nine nines")	10^{-9}	31.5 ms	7.14 mm^2 (≈ pin)
99.99999999% ("ten nines")	10^{-10}	3.15 ms	0.714 mm^2
99.999999999% ("eleven nines")	10^{-11}	315 µs	0.071 mm^2
99.9999999999% ("twelve nines")	10^{-12}	31.5 µs	0.007 mm^2 (≈ a hair)

* The following sizes are considered: soccer field (105 m x 68 m), penalty area (40.32 m x 16.5 m), DIN A4 (21 cm x 29.7 cm), 5€ note (12 cm x 6.2 cm), postage stamp (2 cm x 3 cm), diameter of the head of a pin (3 mm), thickness of a human hair (0.05 mm).

degrades the quality of service but does not have dramatic consequences. In such a system, mean values and distribution shapes are typically considered as performance metrics. In contrast, in a hard real-time system, a delayed execution of a task reduces the utility of the task's results to zero and can lead to a complete failure of the system; hence, worst-case values are of interest instead of mean values. Furthermore, to prevent damages or catastrophes, certain mechanisms may be installed to switch the system into a fail-safe mode in case of a missed execution deadline. In [Pop14], the idea of a degradable service for URLLC is introduced, with the service type being adapted according to the available connection quality.

2.2 Exemplary Use Cases

In addition to traditional services and business models of mobile networks, a multitude of new applications in other industries and vertical markets are envisioned for 5G networks [5GP16]. As explained in Section 1.1, three different application categories have been discussed recently.

This thesis focuses on URLLC requiring high reliability and low latency. Some exemplary use cases and their respective requirements are listed in Tab. 2.2. All the presented use cases have in common that they are not mainly about communication of content but about steering and controlling objects in real-time. Furthermore, the use cases belong to the group of hard real-time systems. Since some environments are dangerous and failures may constitute a risk to the