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ACCESS AND BACKHAUL SOLUTIONS FOR CELLULAR-ENABLED INDUSTRIAL WEARABLES

SHORTENED VERSION OF PH.D. THESIS

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1 INTRODUCTION

Several industries are undergoing a digital transformation to address the challenges of rising safety and efficiency standards and ensure that their products, services, and business processes are future-proof to meet these demands. The journey toward digitilized industries has already started but has gained even more attention during the Covid-19 pandemic [1]. Prospective use cases for industrial automation clearly show the need for a reliable, low-latency, and high-performance wireless communication infrastructure to support the requirements of these novel use cases [2]. The limitations of legacy wired and wireless unlicensed-spectrum technologies deployed in industries drive the trend toward the use of cellular connectivity for industrial automation [3]. Designed with the aim of supporting automated vertical domains, Fifth-Generation (5G) and Beyond 5G (B5G) technologies are considered to be able to address the advanced connectivity requirements of emerging use cases in several sectors, such as the manufacturing and maritime industries.

An important component of these connected and automated industries is the employment of intelligent assistant systems [4]. As part of the intelligent assistant systems or “smart helpers”, industrial wearables are expected to play a major role in the emerging use cases for industrial automation [5]. They can be utilized in a variety of use cases and applications to improve workforce productivity, safety, and efficiency in several sectors [6]. As the relay-assisted operation may not always provide wearable devices with the desired always-on connectivity, they can function in a standalone mode using long-range cellular communications [7]. This paves the way for cellular-enabled wearable devices that can be integrated into industrial setups to provide workers with the needed efficient hands-free operation, while encompassing advanced sensors and offering important insights about the productivity, safety, and health condition of workers.

1.1 Thesis motivation and aim

The market trends and standardization efforts reviewed as part of this research work emphasize that employing cellular-enabled industrial wearables provides businesses with the benefits of both wearable technology and cellular connectivity. However, these benefits can only be tapped into if the technology specified by the 3rd Generation Partnership Project (3GPP) meets the application requirements while taking into account the novel industrial setups, communication scenarios, and device capabilities. Hence, it is important to first understand the requirements of industrial wearable applications and assess the applicability of the cellular solutions dedicated to the support of wearable communications to such applications. Recognizing the challenges in highly dynamic industrial environments, it is essential to enhance the communications between the wearable devices and the cellular network in an end-to-end manner with solutions for both the access and the backhaul segments.

The goals described above show that more research work is needed to achieve these stepping stones toward the concrete implementation of efficient communication solutions for cellular-enabled industrial wearables, especially given that more attention from the research community has long been directed to consumer wearables with more focus on relay-assisted communications and short-range unlicensed-spectrum technologies like Bluetooth Low Energy (BLE), Wireless Fidelity (Wi-Fi), Radio Frequency Identification (RFID), Near-Field Communication (NFC), and Zigbee [8–10]. These technology and literature gaps motivate this research work to advance the use of cellular-enabled industrial wearables and highlight their significant role in the digitalization and automation of different vertical domains. Hence, this thesis aims to **assess the applicability of cellular connectivity to industrial applications with cellular-enabled wearables and develop efficient access and backhaul solutions for the support of the emerging application requirements.**

1.2 Research objectives and methodology

To achieve the aim of the thesis, three main *Research Objectives* (ROx) have been formulated as follows with their corresponding *Research Questions* (RQx).

RO1. Assess the applicability of cellular connectivity to emerging industrial wearable applications.

- **RQ1.1.** *How to characterize the requirements of the emerging industrial applications with Reduced-Capability (RedCap) wearables?*
- **RQ1.2.** *Are the device features recommended by 3GPP for RedCap wearables able to satisfy the anticipated requirements?*

RO2. Improve the Radio Access Network (RAN) performance for cellular-enabled industrial wearables.

- **RQ2.1.** *How can RedCap wearable devices benefit from additional cellular features for improved RAN performance?*
- **RQ2.2.** *To what extent can the proposed access solutions enhance the RedCap wearable communications?*

RO3. Develop intelligent backhaul and networking solutions in constrained communication setups.

- **RQ3.1.** *What are the main issues for backhaul communications in industrial networks and how to resolve them?*
- **RQ3.2.** *How can the massive data generated over industrial networks and timely information on their dynamics be leveraged to boost their sustainability while satisfying the application requirements?*

To answer the above questions and thus attain the outlined objectives, a general strategy was adopted in this dissertation work with subsequent stages leading to the key contributions to be introduced in the following subsection. In the first step, the recent technologies specified in standards and the methods proposed in research works in connection with the tackled research objectives are studied to identify the main challenges. A research hypothesis is formulated after an investigation of the challenge identified in the previous step. To understand the behavior and dynamics of the targeted communication system, predict its performance, and verify the formulated hypothesis, a simulation model is built using the associated communication scenarios and parameters. Network Simulator 3 (ns-3) and MATLAB have been the main tools utilized to build simulation models in this work, when adopting this first research method. In the second research method adopted in this thesis, capable mathematical tools are needed to analyze the key problems arising from challenging use cases and recent solutions and methods available in the literature. Markov Decision Process (MDP) has been the main mathematical framework for decision-making used in this work and validated by employing the MATLAB simulator. In the final stage, conclusions about the tackled research objectives are drawn, main results are submitted to the research community for peer review, and directions for addressing further research objectives are offered.

1.3 Key contributions

The main *Contributions* (Cx) of the thesis are organized in three groups mapped onto the three research objectives formulated in Subsection 1.2.

C1. Applicability assessment.

- **C1.1.** Introduction of novel Industrial Mid-End Wearable Applications (IM-EWA) and definition of their requirements.
- **C1.2.** Assessment of the applicability of Reduced-Capability New Radio (NR RedCap) to IM-EWA.

C2. Access solutions and enhancements.

- **C2.1.** RedCap wearable communication improvement with Device-to-Device (D2D) capabilities.
- **C2.2.** Uplink (UL) performance enhancement with Supplementary Uplink (SUL).

C3. Backhaul and networking solutions.

- **C3.1.** Model-based solution for efficient backhaul selection.
- **C3.2.** Data-driven approach for intelligent industrial networking.

For peer review and result verification, the author of this thesis documented and disseminated the essentials of the above contributions in the form of scientific publications in well-recognized journals and proceedings of international conferences. References to published works by the main author of the thesis are utilized throughout the following sections, including both the papers summarizing the main contributions of the dissertation [11–16] and the remaining publications produced during the Ph.D. period [6,9,17,18].

This short version of the thesis covers the most significant developments achieved while targeting the research objectives **RO1**, **RO2**, and **RO3** as stated in Subsection 1.2. It consists of five sections, where, in addition to the present Section 1 and the concluding Section 5, the three core sections summarize the three groups of contributions (**C1**, **C2**, and **C3**), respectively.

2 CELLULAR CONNECTIVITY FOR INDUSTRIAL WEARABLES

An essential and distinctive feature of a wearable device is its small form factor that dictates the use of miniature batteries, limited number of antennas, and small-sized power amplifiers. In light of these factors, manufacturers have preferred short-range radio technologies, such as Bluetooth and Wi-Fi, over cellular Long-Term Evolution (LTE) which was originally intended for the delivery of high data rates [7]. As a result, 3GPP was prompted to suggest using existing cellular solutions and in the subsequent phase endorse new technologies to facilitate wearable device communications over cellular networks. The existing cellular solutions include D2D communications [19] and Low-Power Wide-Area (LPWA) technologies [8]. In the recent 3GPP Release 17, a new communication class that defines the required technical capabilities to address the mid-end Internet of Things (IoT) applications was introduced [20]. It was initially named NR-Lite, subsequently re-named to NR-Light, and finally established as NR RedCap. RedCap devices can include more advanced meters, industrial sensors, surveillance cameras, and wearable devices that can be employed in smart home, smart city, and industrial applications [21].

2.1 Requirements of industrial wearable applications

When employed in industrial use cases, RedCap wearables can enable a new range of mid-end applications that target enhanced worker safety and productivity. These applications have relaxed requirements in comparison to high-end Extended Reality (XR) and involve wearable devices with more elaborate features and capabilities when compared to low-end wearables like handheld scanners. As part of the contributions of this thesis, the new range of industrial applications enabled by RedCap wearables is referred to as IM-EWA for industrial mid-end wearable applications. Tab. 2.1 summarizes the main IM-EWA requirements in terms of data rate, latency, and reliability [22–25]. Examples of the potential future applications with RedCap wearables are provided below and categorized by the targeted industrial use cases. The identification of these requirements and application categories answers the research question **RQ1.1**.

Tab. 2.1: Performance requirements of IM-EWA

Requirement	**Ranges**
Data rate	UL: [2-5] Mbps DL: [5-50] Mbps
Latency	[5-100] ms
Reliability	[99-99.99] %

- **IM-EWA for process management.** This category comprises applications aiming to ensure the appropriate execution as well as surveillance of the industrial workflows and processes. Exchanging progress reports using smart watches for better workforce resource management and streaming video tutorials using wearable headsets are examples of applications under this category. The data rates required by such applications have to be higher than what Massive Machine-Type Communications (mMTC) provide, but are lower than Enhanced Mobile Broadband (eMBB) data rates. The ranges given in Tab. 2.1 for the user-experienced data rate (i.e., up to 5 Mbps in the UL and up to 50 Mbps in the Downlink (DL)) can provide the quality needed for this category of applications.

- **IM-EWA for work safety.** Wristbands controlling the usage of potentially dangerous power tools, wearable headsets alerting truck drivers when sensing fatigue or distraction, and Mission-Critical Push-To-Talk (MCPTT)-enabled smart watches used to establish calls in critical situations are all applications that provide workers with real-time safety measures to efficiently prevent work accidents and respond to emergencies. From the communication perspective, such fast response to accidents and emergencies requires low End-to-End (E2E) latency, e.g., values between 5 and 10 ms from the range defined in Tab. 2.1.
- **IM-EWA for healthcare monitoring.** It is essential to prioritize the well-being of the workforce and ensure healthy work spaces, given the direct impact of mental and physical health on productivity. Although wearable devices like fitness trackers and health monitors have been long used by consumers, their benefits can be augmented in industrial applications by hosting more advanced functionalities that should allow smart factories to not only provide their workers with insights around monitoring their health conditions, but also alleviate the typical administrative burden related to the processing of insurance and billing statements. Since it involves exchanging health-related data, high communication reliability is required for this category of applications, e.g., values between 99.9% and 99.99% from the range set in Tab. 2.1.

2.2 NR RedCap for industrial wearables

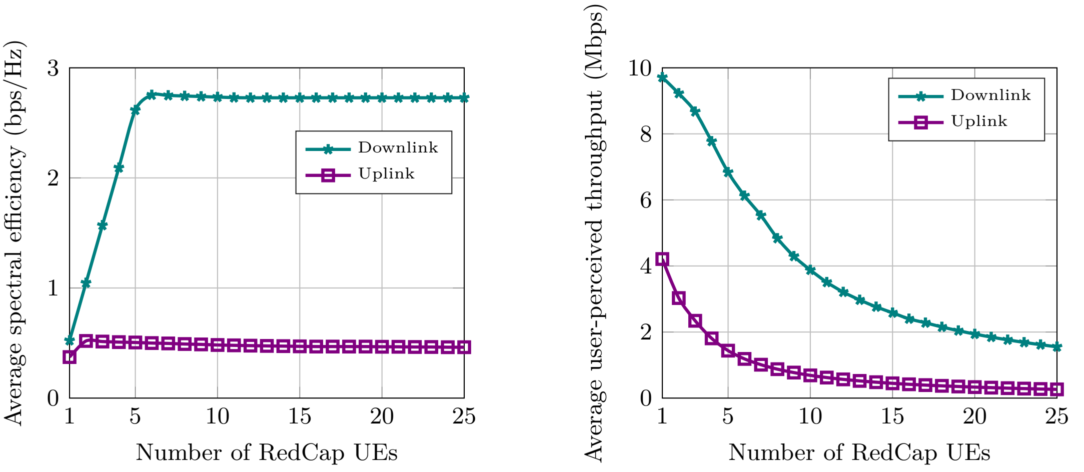
In this section, the network performance in terms of the IM-EWA requirements discussed above is evaluated using the combination of User Equipment (UE) features recommended by 3GPP. The output of the performance evaluation should help answer the question of whether this combination of features satisfies the targeted application requirements. The ns-3 tool was used for this applicability assessment to evaluate the network performance when deploying RedCap wearable devices with the combination of features given in Tab. 2.2.

Tab. 2.2: Combination of RedCap UE features considered in the applicability assessment

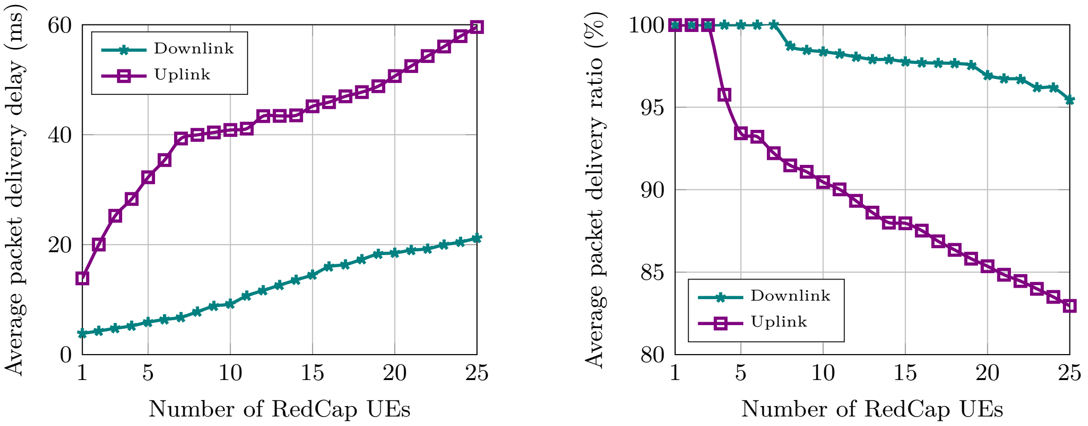
Feature	**Value**
Bandwidth	20 MHz
Antenna configuration	1Rx/1Tx
Number of DL layers	1
Maximum UL modulation order	4 (16QAM)
Maximum DL modulation order	6 (64QAM)
Decoding time (N1)	20 symbols
Preparation time (N2)	24 symbols

In terms of frequency-related assumptions, the RedCap wearables considered in the subsequent performance evaluation operate in Frequency Range 1 (FR1) Time-Division Duplexing (TDD) with the Sub-Carrier Spacing (SCS) of 30 kHz, which is a scenario widely considered for smart factory deployments. In the NR RedCap specification [22], both full buffer and non-full buffer (or bursty) traffic models are considered in the System-Level Simulation (SLS)-based evaluations regarding the effects of UE complexity reduction on the network capacity and the spectral efficiency performance. Hence, these two types of models are assumed in this applicability assessment, which starts with the full buffer traffic evaluation using the average spectral efficiency as the main Key Performance Indicator (KPI). The latter is the aggregated throughput of all the considered RedCap UEs divided by the channel bandwidth [26] and is given in Fig. 2.1a. Subsequently, Fig. 2.1b, Fig. 2.1c, and Fig. 2.1d report the numerical results for the bursty traffic evaluation.

The first KPI used in this applicability assessment for the bursty traffic evaluation is the average user-perceived throughput with the UL and DL results reported in Fig. 2.1b. The results for the average packet delivery delay experienced by the considered RedCap wearables in the DL and the UL transmissions with bursty traffic are reported in Fig. 2.1c. Measured as the ratio of the total number of packets delivered to the destination to the total number of packets sent from the source, the results for the average DL and UL packet delivery ratio are reported in Fig. 2.1d. These KPIs are assessed as a function of the number of RedCap UEs to understand the system load under which the IM-EWA requirements defined in Tab. 2.1 can be satisfied by the assumed UE features.



(a) Spectral efficiency ; full buffer traffic (b) User-perceived throughput ; bursty traffic



(c) Packet delivery delay ; bursty traffic (d) Packet delivery ratio ; bursty traffic

Fig. 2.1: UL and DL performance achieved by RedCap UEs

As a summary of the conducted applicability assessment, RedCap wearables with the assumed combination of features in Tab. 2.2 can achieve the IM-EWA requirements defined in Tab. 2.1, but this achievement depends highly on the traffic configuration (i.e., full buffer or bursty traffic models) and the system load (i.e., number of RedCap UEs). Tab. 2.3 summarizes the main output of this applicability assessment (i.e., the answer to the research question **RQ1.2**).

Tab. 2.3: Main output of the applicability assessment

IM-EWA requirement	**Ranges**	**Assessment results for the full buffer traffic models**	**Assessment results for the bursty traffic models**
Data rate	UL: [2-5] Mbps DL: [5-50] Mbps	UL: requirement fulfilled in setups with up to 5 RedCap UEs DL: requirement fulfilled in setups with up to 10 RedCap UEs	UL: requirement fulfilled in setups with up to 3 RedCap UEs DL: requirement fulfilled in setups with up to 7 RedCap UEs
Latency	[5-100] ms	-	UL and DL: requirement fulfilled for the system loads considered in this thesis (up to 25 RedCap UEs) UL: [5-10] ms: requirement unfulfilled (even in the setup with 1 RedCap UE) DL: [5-10] ms: requirement fulfilled in setups with up to 10 RedCap UEs
Reliability	[99-99.99] %	-	UL: requirement fulfilled in setups with up to 3 RedCap UEs DL: requirement fulfilled in setups with up to 7 RedCap UEs

3 NETWORK ACCESS SOLUTIONS FOR REDCAP INDUSTRIAL WEARABLES

The categories of IM-EWA defined in Section 2 promise not only enhanced productivity but also improved safety and health conditions of workers. RedCap wearables have to therefore be provided with the required connectivity levels in cellular-enabled smart factories, especially in scenarios where the success of tasks can be affected by the reduced capabilities of devices and/or the challenges of industrial environments. Based on this understanding, this section proposes enhancing the RAN performance by extending the communication capabilities of RedCap wearables with appropriate cellular features.

3.1 D2D-aided NR RedCap

Employed as a complement to traditional cellular connectivity, D2D communications proved their benefits in several use cases (e.g., mission-critical public safety [27], Vehicle-to-Everything (V2X) services [28], ship-to-ship communications [29], IoT [30], and wearables [19]) and in terms of multiple performance metrics (e.g., spectral efficiency [31], UE throughput [32], energy efficiency [33], coverage probability [34], content acquisition delay [35], and packet loss ratio [36]). To exploit these benefits, the thesis proposes aiding the cellular access links between RedCap wearables and the Base Station (BS) with D2D communications. Several scenarios suggest that D2D communications can work in concert with cellular links to enhance the connectivity options and the network access experience for RedCap wearables. To validate this hypothesis, the D2D-enhanced RAN performance was investigated.

The system-level performance evaluation was conducted using ns-3 as the simulation tool, specifically the ns-3 D2D module [37]. The employed ns-3 module was extended with the essential features for the modeling of wearable communications in industrial setups. In terms of the device capabilities, the complexity reduction features were implemented as recommended by 3GPP for RedCap devices operating in FR1 [22]. Two scenarios were considered in this performance evaluation, where cellular communications between the RedCap wearables and the BS are complemented with direct D2D and UE-to-network relay links. To examine the impact of employing direct D2D communications by RedCap wearables in a single-cell scenario, the area spectral efficiency is evaluated. The latter characterizes the sum of the maximum data rates achieved in a cell per unit bandwidth per unit area in bps/Hz/m^2 [38]. Fig. 3.1 reports the numerical results for the area spectral efficiency and its variation by following the total and D2D user densities. As depicted in Fig. 3.1, the obtained results confirm the advantages of complementing the cellular connectivity of RedCap wearables with D2D communications, specifically for the network capacity improvement. These findings gain more importance in factory environments where the number of devices can increase dramatically and the cellular network is expected to handle such surge of demand without introducing bottlenecks.

The packet delivery ratio is the application-related KPI considered for the evaluation of the service reliability in cellular and D2D-aided connectivity scenarios with UE-to-network relaying. In addition to the connectivity scenarios (i.e., with and without D2D relaying) and the packet size, Fig. 3.2 and Fig. 3.3 report the numerical results for the packet delivery ratio depending on the Reference Signal Received Power (RSRP) threshold considered for enabling the UE-to-network relay service and the

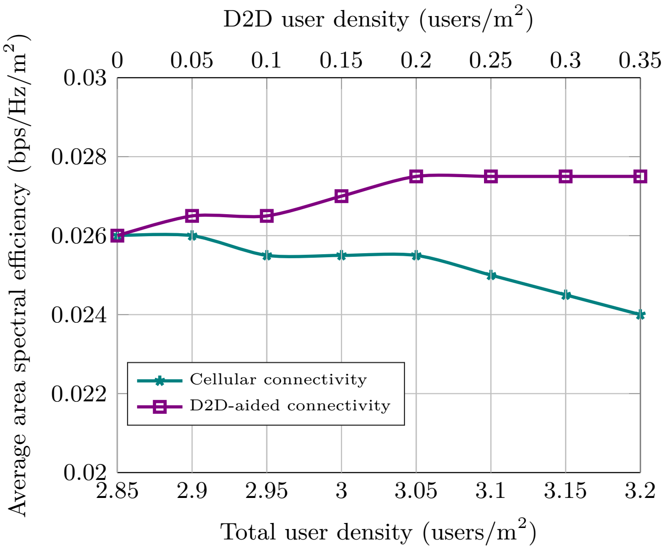


Fig. 3.1: Area spectral efficiency in single-cell in-coverage industrial communication scenario with RedCap wearables [15]

Modulation and Coding Scheme (MCS) utilized for sidelink transmissions, respectively. The main observation from Fig. 3.2 and Fig. 3.3 is that the share of successfully delivered packets in the D2D-aided scenarios is generally higher than that in the direct cellular connectivity setup. The rationale here is that by deploying D2D links to the relay UEs, remote RedCap wearables can improve their service continuity. These higher reliability results can be improved further by enabling the UE-to-network relay service in a proactive manner (i.e., before experiencing lower values of the primary cell's Reference Signal Received Power (RSRP)) and adopting sidelink configurations with higher MCS.

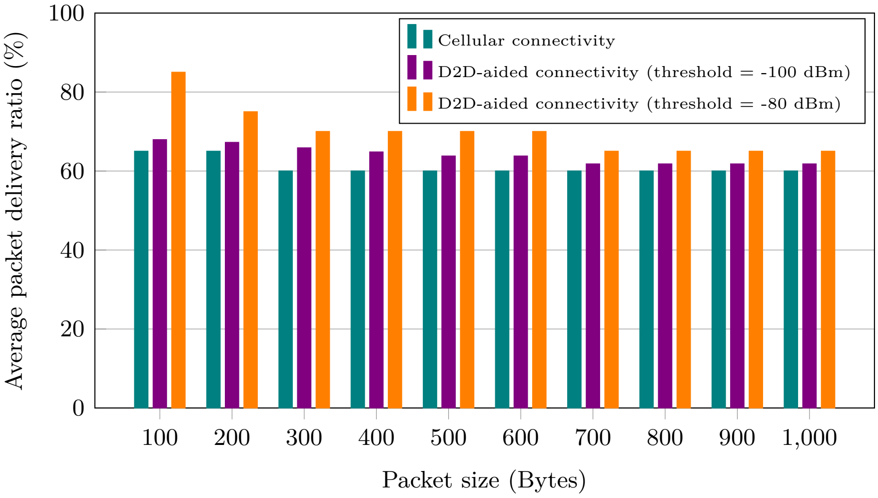


Fig. 3.2: Packet delivery ratio in communication scenarios with and without D2D relaying for RedCap wearables (Sidelink MCS = 10)

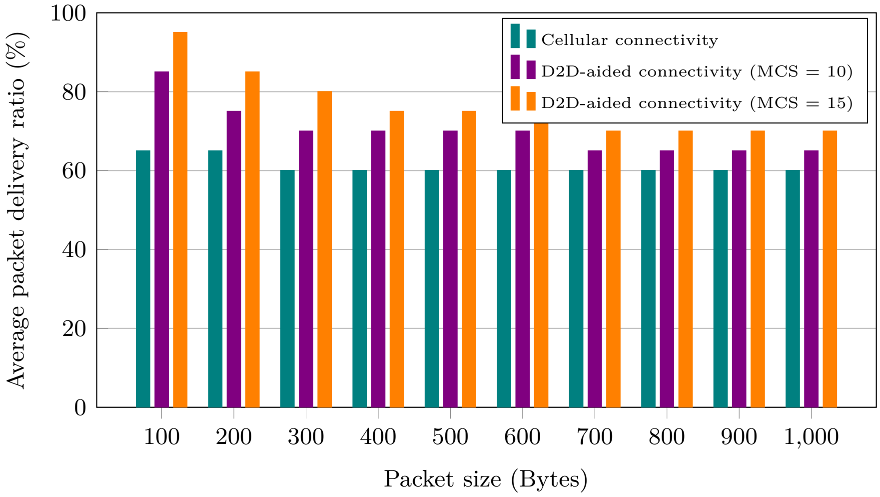


Fig. 3.3: Packet delivery ratio in communication scenarios with and without D2D relaying for RedCap wearables (RSRP threshold = -80 dBm) [15]

3.2 UL performance enhancement with SUL

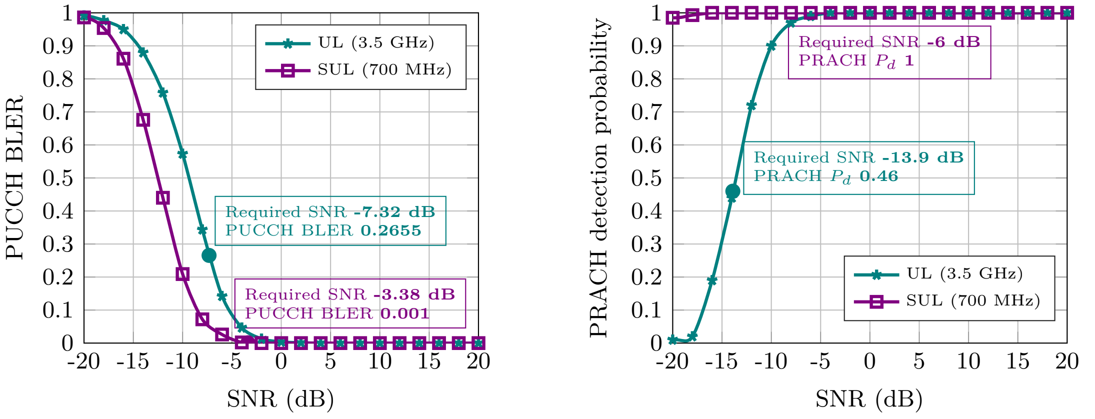
This work studies the multi-band operation of RedCap devices and proposes a solution for UL performance enhancement of NR RedCap by selecting the technologies among Dual Connectivity (DC), Carrier Aggregation (CA), and SUL that industrial RedCap wearables can use with respect to the 3GPP recommendations for complexity reduction. Based on the conducted study, this work advocates for the use of SUL by Release 17 RedCap devices to achieve better UL performance. This technology can be beneficial for NR RedCap in mid-band TDD without increasing the device complexity (i.e., device cost). Another motivation is the gap in the UL performance between Release 15 New Radio (NR) devices and RedCap devices, if the latter do not support the existing features for UL enhancement. To narrow this gap, the network may need to employ advanced and more complex scheduling mechanisms to separately handle devices with dissimilar capabilities. Hence, using SUL by RedCap devices helps not only improve the UL performance without additional costs but also avoid the need for the above extra mechanisms.

The NR RedCap performance when using TDD UL and Frequency-Division Duplexing (FDD) SUL was evaluated and the main findings of this evaluation are summarized below. This evaluation aims to confirm the performance gains for RedCap devices using the three 5G UL physical channels; Physical Uplink Shared Channel (PUSCH), Physical Uplink Control Channel (PUCCH), and Physical Random Access Channel (PRACH). Specifically, the gains of SUL in terms of PUSCH Maximum Coupling Loss (MCL), PUCCH Block Error Rate (BLER), and PRACH detection probability are assessed using the 5G toolbox of MATLAB, which provides standard-compliant functions for the modeling of NR communication systems. The Link-Level Simulation (LLS) results for the PUSCH MCL obtained for UL and SUL are provided in Tab. 3.1. As evident from the obtained results, SUL provides better PUSCH coverage than UL. It can achieve 8.33 dB coverage gain, which confirms the benefits of using SUL by RedCap UEs at lower frequencies since the coverage in the low-bands is better than that in the mid-bands [39].

Tab. 3.1: PUSCH coverage gain of SUL [13]

Carrier frequency	**Required SNR**	**PUSCH MCL**	**MCL gain**
UL (3.5 GHz)	7 dB	114.29 dB	8.33 dB
SUL (700 MHz)	10.6 dB	122.62 dB	

Along with the PUSCH MCL, the BLER of Uplink Control Information (UCI) transmitted over the PUCCH format 3 and the probability of detection of PRACH preambles (P_d) for 5G NR UL and SUL are assessed in Fig. 3.4a and Fig. 3.4b, respectively. The learning from Fig. 3.4a is that SUL for PUCCH communications helps achieve not only lower BLER than that in the TDD UL but also the 1% target performance of PUCCH BLER as specified by 3GPP [40]. Fig. 3.4b shows that using the 700 MHz SUL provides better P_d values than those for the case of 3.5 GHz UL and that the 99% target performance is achieved by the SUL ($P_d = 100\%$), while UL provides a lower value than the target probability of detection ($P_d = 46\% < 99\%$) at the required Signal-to-Noise Ratio (SNR).



(a) PUCCH BLER

(b) Detection probability of PRACH preambles

Fig. 3.4: UL and SUL performance for RedCap wearables [13]

3.3 D2D and SUL use cases for NR RedCap

Subsections 3.1 and 3.2 provide an answer to the research question **RQ2.1**, where the proposed solutions for enhanced RAN performance for RedCap wearable devices included D2D communications and SUL functions. Based on the fact that adding an extra device capability has its benefits and costs, this work also examined, as part of the answer to the research question **RQ2.2**, whether employing D2D and SUL by RedCap wearables can incur any degradation in the RAN performance. The obtained SLS-based evaluation results suggest that the D2D relaying solution can be employed by RedCap wearables in UL-centric applications and may not be suitable for applications with tight constraints on the DL performance. Regarding SUL, the obtained LLS results suggest that it can be employed by RedCap wearable devices that observe a high probability of moving outside of coverage of NR UL (e.g., highly mobile users in a factory) and that generate elastic traffic. This extended evaluation improves the understanding of the extent to which these solutions are beneficial for the considered constrained devices and industrial communications.

4 SOLUTIONS FOR EFFICIENT BACKHAUL AND INDUSTRIAL NETWORKING

Cellular-enabled maritime networks, named 6G Maritime Networks (6G-MNs) in this thesis, provide an illustrative example of complex and integrated industrial setups, where RedCap wearables can be employed among the multitude of industrial intelligent assistant systems. Recognizing that the deployment of terrestrial and Non-Terrestrial Networks (NTNs) in 6G-MNs necessitates a selection from the available wireless backhaul solutions, which have dissimilar data transmission costs and communication link qualities, the backhaul selection has been identified as a key issue in integrated terrestrial and non-terrestrial maritime networks with different cost considerations and time-sensitive application requirements. This section shows that the desired trade-off between the data transmission expenses and the timely throughput guarantees can be achieved with an MDP-based solution for backhaul selection. Beyond developing model-based solutions for intelligent decision-making, this thesis advocates for the use of Artificial Intelligence (AI) and Machine Learning (ML) to cope with the increased complexity of managing integrated communication systems, such as 6G-MNs.

4.1 Proposed solution for backhaul selection

The considered maritime communication scenario is based on an integrated terrestrial and non-terrestrial cellular network supporting near-shore maritime communications. The network comprises a terrestrial infrastructure (i.e., Terrestrial BS (TBS) and Ground Station (GS) for satellite communications) and a non-terrestrial segment (i.e., UAV-mounted BS (UBS) and satellite). Hence, it offers the Vessel-mounted BS (VBS) three options for wireless backhaul relaying: direct backhaul to the TBS, two-hop backhaul via UBS, or two-hop backhaul via Low Earth Orbit (LEO) satellite. The backhaul selection problem was formulated as a periodic decision making problem with stochastic states and a cost function to minimize. Hence, the problem in (4.1) lends itself to an MDP consideration with infinite horizon. The four components of the MDP framework (i.e., states, actions, transition probabilities, and costs) were detailed in the thesis to provide a formulation for the backhaul selection problem and obtain the optimal policy. Subsequently, the value iteration method was applied to guarantee the ϵ-optimality of the obtained stationary policy for backhaul selection over a finite number of iterations. As the value iteration algorithm can be not only time-consuming but also resource-consuming, this work derived a lightweight heuristic solution for backhaul selection from the ϵ-optimal policy computed using the value iteration algorithm.

$$\begin{gathered}\underset{\pi\in\Pi}{\text{Minimize}}\ \mathbb{E}_\pi\left[\sum_{t=1}^{\infty}\gamma^{t-1}\left[\frac{m\Big(d(s_t,\pi(s_t))\Big)}{\max(m_a)Q}+\epsilon\Big(d(s_t,\pi(s_t))\Big)\right]\right],\\ \max(m_a)\triangleq\max(m_1,\dots,m_{|\mathcal{A}|}),\end{gathered}\tag{4.1}$$

where π denotes a feasible policy that specifies the selected backhaul a_t in system state s_t (i.e., $a_t = \pi(s_t)$), $\mathbb{E}_\pi[\cdot]$ is the expectation with respect to the probability distribution of policy π, γ is the discount factor, $d(s_t, a_t)$ denotes the expected number of delivered data units in state s_t if backhaul a_t is selected at time slot t, $m(d(s_t, a_t)) \triangleq m_a d(s_t, a_t)$ is the immediate cost of using backhaul a_t in state

s_t, m_a is a known monetary cost per data unit transmission over backhaul a, Q is the number of data units in the backlog queue of the VBS, and $\epsilon(d(s_t, a_t))$ denotes the penalty incurred if the outcome of a transmission $d(s_t, a_t)$ violates the timely throughput requirement.

In the performance evaluation of the obtained policies, the MDP-based solution and the heuristic solution were compared with greedy approaches for backhaul selection. In the considered scenario, a greedy policy can always select the backhaul with the minimum monetary cost of data transmission (referred to as MinCost) or select the option with the highest SNR disregarding the monetary cost (named MaxSNR). The KPIs utilized in this comparison were cost efficiency (Fig. 4.1), which is defined as the number of data units delivered within the deadline per unit of monetary cost, and timely throughput (Fig. 4.2). In Fig. 4.1, the cost per data unit transmission via TBS (m_{TBS}) varies, while the costs of the two remaining options are updated accordingly considering the figures based on the existing microwave and satellite backhaul deployments. Fig. 4.2 reports the obtained results for the timely throughput as a function of the number of data units Q.

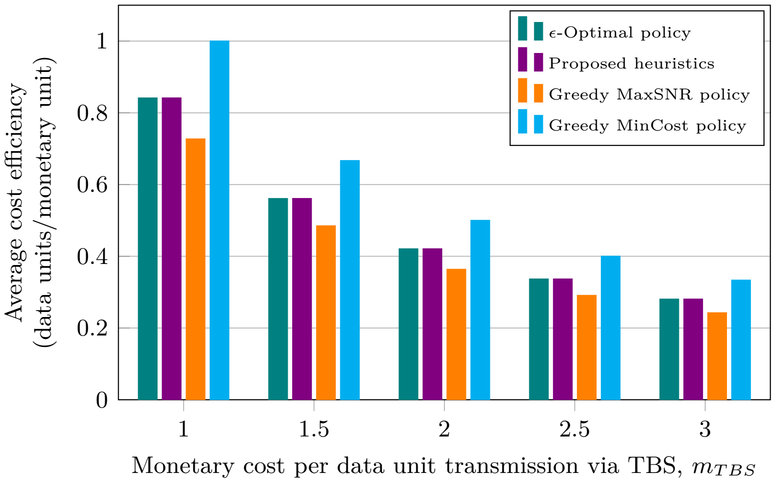


Fig. 4.1: Assessment of system cost efficiency for all proposed and reference policies [11]

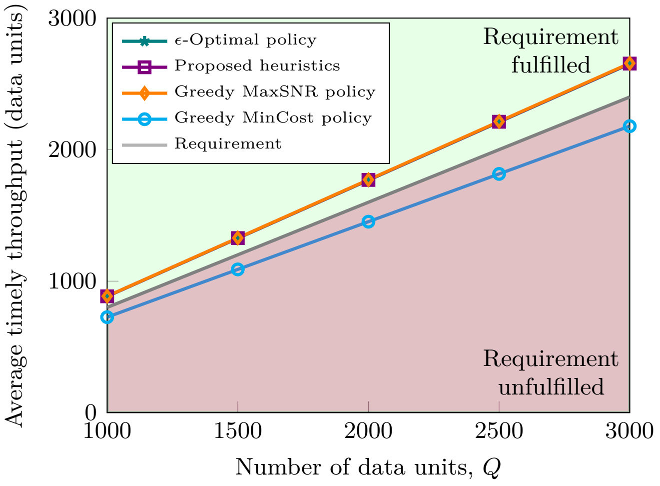


Fig. 4.2: Timely throughput achieved for all proposed and reference policies [11]

As reported in Fig. 4.1 and Fig. 4.2, the output of the proposed heuristics approaches the results of the ϵ-optimal policy for the varied monetary cost m_{TBS} and the traffic demand Q. Therefore, the proposed heuristics demonstrate near-optimal performance under a wide range of key system parameters. By applying the proposed heuristics, the system can make more cost-efficient decisions for backhaul selection than when following the MaxSNR strategy (see Fig. 4.1). These two policies help the system meet the timely throughput requirement in contrast to the MinCost approach, as demonstrated in Fig. 4.2. Hence, the heuristic solution proposed in this work provides the system with better cost efficiency than the MaxSNR strategy and with higher timely throughput than the MinCost approach. This confirms the benefits of taking into account both cost and loss rate factors in the backhaul selection as well as the limitations of making a decision based solely on signal quality or monetary cost.

4.2 Data-driven industrial networking

Beyond application data used for infotainment and maritime navigation and logistics, a large volume of data regarding the operation of the network is generated over 6G-MNs, including (i) user profile data such as device position, mobility, transmission, and energy consumption patterns, (ii) network configuration data encompassing instantaneous link capacity and resource utilization, and node capabilities, and (iii) service data covering quality of experience and capabilities for execution of offloaded tasks. Allowing to extract valuable information from these massive data, AI techniques can be used to predict traffic peaks and system demands, detect anomalies or near-overload conditions, and identify nodes or clusters with high energy and resource consumption.

Fig. 4.3 illustrates the envisaged AI-aided 6G-MN, which comprises three main components. The first component is a high-performance terrestrial network segment that efficiently manages the fleet and supports the operation and maintenance of smart harbors and industrial ports. The second component is in the non-terrestrial part that encompasses dynamic multi-hop topologies, e.g., based on Integrated Access and Backhaul (IAB), to ensure the connectivity between the vessels and the terrestrial segment and the ubiquitous monitoring of inland, near-shore, and offshore areas for improved human and marine life safety. The third and the last component of the envisaged AI-aided Sixth-Generation (6G) system is a powerful edge and cloud infrastructure for centralized and distributed learning to enable proactive resource and topology management for sustainable maritime operations.

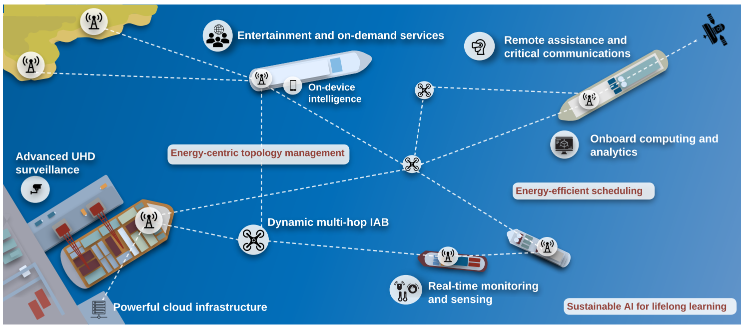


Fig. 4.3: AI-aided 6G system with integrated features for sustainable maritime operations [12]

Utilizing suitable ML techniques facilitates the design of self-optimized and automated 6G-MNs.

Examples of AI applications in 6G-MNs were provided in this work to resolve topology management and scheduling issues with energy-oriented optimization goals. Fig. 4.4 and Fig. 4.5 report the SLS results obtained as part of this thesis while evaluating the Deep Neural Network (DNN)-based approach for joint routing and scheduling and the Long Short-Term Memory (LSTM)-based approach for Channel Quality Indicator (CQI) prediction, respectively. As demonstrated in Fig. 4.4, the considered multi-hop maritime communication scenario can display higher energy efficiency by employing DNNs for reducing the number of links involved in the routing and scheduling decisions. Complementing the results summarized above for the topology management use case, Fig. 4.5 shows that not only the system energy efficiency can be improved with better channel quality predictions, but also the end-to-end packet delivery delay may be significantly decreased. These examples of AI applications confirm the significant role of data-driven approaches in the management of complex industrial networks, e.g., 6G-MNs. However, additional considerations, such as distributed learning mechanisms and device-level solutions, can be taken into account to fully exploit the benefits of the data-driven approaches in terms of both the sustainability targets and the emerging industrial application requirements.

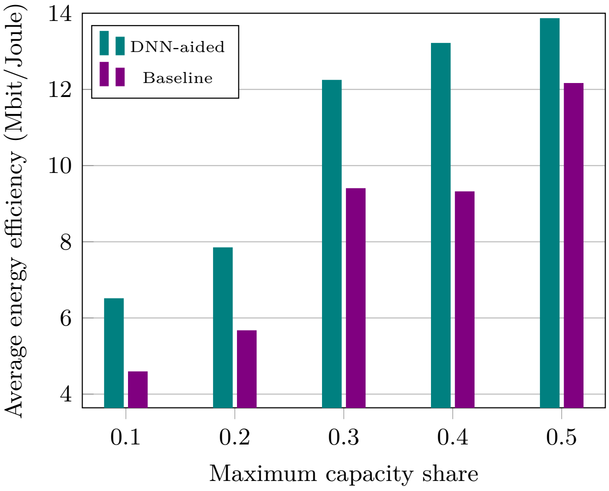


Fig. 4.4: Use of DNN for energy-efficient topology management [12]

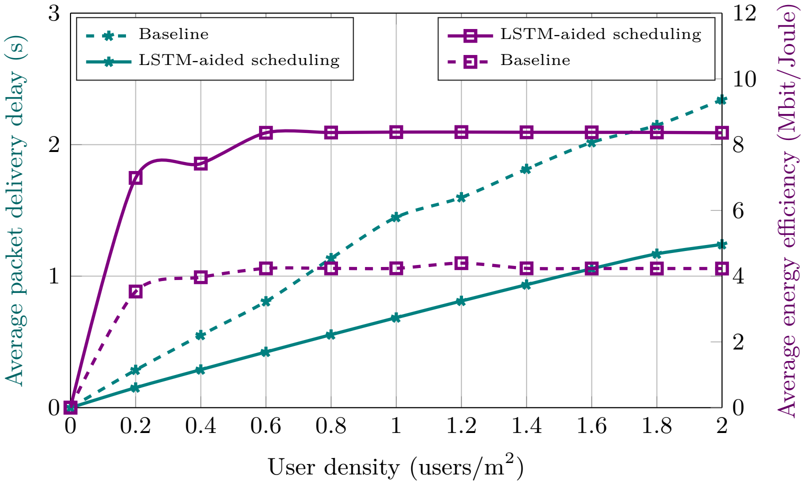


Fig. 4.5: Use of LSTM for energy-efficient real-time scheduling [12]

5 CONCLUSIONS AND FUTURE DIRECTIONS

To demonstrate how the research objectives set in Section 1 are met in this thesis, important conclusions and main observations are summarized in the following list.

- NR RedCap-enabled wearable devices can be involved in industrial applications with mid-end requirements that fall in-between the two extremes of high-end eMBB/Ultra-Reliable Low-Latency Communications (URLLC) and low-end mMTC. Named IM-EWA in this thesis, this novel category of applications can target industrial process management, workforce safety, and healthcare monitoring in cellular-enabled industrial networks and pose different requirements in terms of data rate, latency, and reliability.
- The RedCap UE configuration recommended by 3GPP for wearable devices is able to satisfy the expected requirements of the novel industrial mid-end wearable applications in the TDD regime with different traffic configurations (i.e., full buffer or bursty traffic models) and system loads (i.e., number of RedCap UEs). This UE configuration may, however, not be suitable for safety-related applications with stringent latency requirements, especially in the UL.
- Employing direct D2D communications between the RedCap wearable devices can offer a viable alternative to network infrastructure densification in cellular-enabled smart factories. In addition, RedCap wearables can attain a gain of up to 50% in the UL packet delivery ratio by utilizing D2D relaying with the appropriately adjusted sidelink configurations.
- Among the solutions introduced by 3GPP for UL performance enhancement, RedCap wearable devices can employ SUL without compromising the recommendations for complexity reduction. In addition to useful improvements in the BLER and detection probability, a gain of 8.33 dB in the UL coverage can be reached by RedCap wearable devices when employing the SUL.
- Cellular-enabled maritime networks, named 6G-MNs in this thesis, provide an illustrative example of complex and integrated industrial setups, where RedCap wearables can be employed among the multitude of industrial intelligent assistant systems. The backhaul selection has been identified as a key issue in integrated terrestrial and non-terrestrial maritime networks with different cost considerations and time-sensitive application requirements. The desired trade-off between the data transmission expenses and the timely throughput guarantees can be achieved with an MDP-based solution for backhaul selection.
- Complex and integrated industrial networks, such as 6G-MNs, generate a large volume of data. Allowing to extract valuable information from these massive data, ML techniques can be employed to build efficient frameworks for intelligent and sustainable industrial networking. Additional considerations, such as distributed learning mechanisms and device-level solutions, can be taken into account to fully exploit the benefits of the data-driven approaches in terms of both the sustainability targets and the emerging industrial application requirements.

The work on the NR RedCap specification enhancements was approved by 3GPP as part of the Release 18 package. This fact confirms the significance of this technology for the 3GPP-involved industrial stakeholders and their interest in the planned NR RedCap use cases, including RedCap wearables. This dissertation work explores novel industrial applications with cellular-enabled RedCap wearables and develops efficient access and backhaul solutions for the support of their emerging requirements. Some of the contributions of this thesis can be useful for the standardization community to identify the necessary improvements to new technologies. For instance, the confirmed benefits of cellular features like D2D and SUL suggest that they can be added to the set of communication capabilities for RedCap devices, together with the discussions around the multi-band operation and the related use cases. For future research, the NR RedCap technology enhancements in 3GPP Release 18 and the mobile mesh version of the IAB technology, which is particularly relevant for integrated terrestrial and non-terrestrial setups, are considered.

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ABSTRACT

This doctoral thesis proposes “Access and Backhaul Solutions for Cellular-Enabled Industrial Wearables”. Aiming to address the current technology gap behind cellular-enabled industrial wearables, this research work is dedicated to assessing the applicability of cellular connectivity to industrial wearables and developing efficient access and backhaul solutions for the support of the requirements of emerging industrial wearable applications. The main outcomes of this dissertation include (i) a concise technology review capturing the evolution of the recent solutions proposed by the 3rd Generation Partnership Project (3GPP) for wearable devices and communications, (ii) an introduction to novel categories of industrial wearable applications with mid-end requirements that fall in-between the two extremes of high-end and low-end Fifth-Generation (5G) service classes, (iii) an assessment of the applicability of the emerging Reduced-Capability New Radio (NR RedCap) technology to the newly introduced wearable applications, (iv) an extension of the RedCap wearable communications with Device-to-Device (D2D) and Supplementary Uplink (SUL) capabilities for enhanced access network performance, (v) a cost- and delay-efficient backhaul selection solution based on Markov Decision Processes (MDPs) for time-sensitive wearable applications in an integrated terrestrial and non-terrestrial communication scenario, and (vi) a data-driven Artificial Intelligence (AI)-aided approach for the management of complex industrial networks with dissimilar device capabilities, communication solutions, and application requirements. A set of simulation and analytical models is developed in this thesis to assess the relevant key performance indicators as part of the listed contributions.