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Managing Radio and Energy Resources in LTE-Based Military Training Networks

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Abstract

The number of wireless connected devices are growing exponentially and the importance of this research area is growing as well to meet the known and looming challenges and expectations. The 5:th Generation telecommunications standard is partly embodied by the Machine-to-Machine (M2M) and Internet of Things (IoT) technologies and standards to handle a big part of these devices and connections. An example within the IoT paradigm is military training systems where each system can consist of thousands of battery operated mobile devices and their shifting requirements shall be fulfilled in an energy-aware manner to increase battery operating times.

Military training radio networks enables realistic combat training. The services and features provided in commercial telecommunications networks are desirable in these often proprietary and task specific networks, increasing capabilities and functionalities. To facilitate the current and future R&D of LTE based networks for adoption in military training networks and services this doctoral thesis intends to provide the starting ground for the energy-aware LTE based wireless communications. The thesis first presents general solutions on how to meet traffic deadlines in wireless networks for large number of nodes, and then continues with solutions for energy-aware LTE-based communications for the User Equipments (UEs).

The work builds on the problem formulation *how to provide energy-aware resource handling for LTE-based military training networks* from where three research questions are derived. From the research questions we derive different hypotheses and then test these within the investigated area to answer the research questions.

The contributions of this work are within areas of resource handling and power saving for mobile devices. In the first area an admission control using deterministic analysis is proposed fulfilling traffic requirements for military training mobile nodes. This admission control is enhanced for multiple-channel base stations, and evaluated using mobile nodes with different heterogeneous traffic requirements. In the second part energy-awareness is in focus for LTE/LTE-A based networks. The main power saving method for LTE/LTE-A UEs, Discontinuous Reception (DRX) mechanism, is evaluated and models for DRX

in *Idle* and *Connected* state are proposed including metrics for wake-up delay and power saving. Additionally a mean queuing delay analysis is proposed for a variant of the *Connected* state DRX. Using these models and metrics, practical design guidelines for tuning of DRX parameters are proposed, including optimization of DRX parameters for either minimizing delay or maximizing power saving.

Acknowledgments

Thanks to SAAB Training and Simulation, my manager Urban Hallqvist, the current board including Mikael Lidbäck, and following managers Ronny Lembke and Magnus Werner, for enabling and financing this research to build core competence within this area and also for believing in me. A big thanks to the research community for all their combined efforts in expanding the human knowledge.

List of Publications

The thesis summarizes the following papers:

A. H. Ramazanali, M. Jonsson, K. Kunert, and U. Bilstrup, “Military training network with admission control using real-time analysis," in *Proceedings of the IEEE International Workshop on Computer Aided Modeling and Design of Communication Links and Networks (CAMAD)*, Athens, Greece, Dec. 1-3, 2014, pp. 249-254.

   Contribution: The method, the real-time analysis framework and the Matlab simulator were developed by me with initial guidance from supervisor Magnus Jonsson building on previous work. This work is a new contribution to admission control with real-time analysis and fulfills also military training network requirements. For the simulator some code was reused on the real-time analysis part but for the packet level simulation new code was written using structure arrays, improving realization of packets, queues and the analysis. Initial text was written and improved by me after review and improvement by supervisors. Analysis was made by me with some initial guidance.

B. H. Ramazanali, M. Jonsson, A. Vinel, and U. Bilstrup, “Multichannel admission control for military training network," in *Proceedings of the IEEE 18th International Symposium on Real-Time Computing*, Auckland, New Zealand, Apr. 13-17, 2015, pp. 150-157.

   Contribution: The admission control builds on previous work with addition for supporting multiple frequency channels and Frequency Allocation Algorithms (FAAs) in the simulator. The novel parts of the method, the admission control and the simulator were developed independently by me after general discussions with the supervisors. The analysis was made by me with guidance by supervisor Alexey Vinel. The text was written by me, reviewed and improved by supervisor with suggestions on further improvements that was implemented by me. The structure of the presentation was improved by supervisor.

C. H. Ramazanali and A. Vinel, "Performance evaluation of LTE/LTE-A DRX: A Markovian approach," *IEEE Internet of Things Journal, Special Issue on Internet of Things over LTE/LTE-A Network: Theory, Methods, and Case Studies*, vol. 3, no. 3, pp. 386-397, June 2016.

Contribution: Proposition on research area, the method and an initial simple Markov chain model for the Discontinuous Reception (DRX) mechanism was made by the supervisor. This Markov chain model was extended to the reduced and the complete DRX mechanisms, analyzed and solved by me largely independently with guidance from the supervisor to obtain the mean wake-up delay expression through little's law. Guidance was given by the supervisor on how to verify results from the model and the simulator with a third method, by obtaining the stationary probabilities with matrix calculations. Implementation of model and simulator was made by me in Matlab as well as the analysis. A structure for the presentation layout was given by the main supervisor, text was written by me and reviewed by the main supervisor several times. Abstract, first paragraph in introduction and conclusion was written by the main supervisor.

D. H. Ramazanali and A. Vinel, "Mean queuing delay in LTE DRX," *IEEE Wireless Communications Letters*, vol. 5, no. 4, pp. 444-447, Aug. 2016.

Contribution: Proposal to obtain mean queuing delay in DRX was made by me. Supervisor suggested to use mean wake-up delay to simplify the calculation. The problem of two component delay was detected and solved by me after discussions with the supervisor. Thereafter, the mathematical derivations for the mean queuing delay together with simulation and verification was made, also by me. Paper was revised on several instances and before last submission a revision was made by supervisor where also a scheduling delay section was added after reviewer comments.

E. H. Ramazanali and A. Vinel, "Tuning of LTE/LTE-A DRX parameters," in *Proceedings of the IEEE International Workshop on Computer Aided Modeling and Design of Communication Links and Networks(CAMAD)*, Toronto, Canada, Oct. 23-25, 2016, pp. 95-100.

Contribution: The proposal for parameters tuning was made by me and discussions landed in this optimization proposal. The Simulator was developed by me and the text was written by me largely independently but with feedback from the supervisor at late stages.

F. H. Ramazanali, A. Vinel, E. Yavuz and M. Jonsson "Modeling of LTE DRX in RRC idle state," *Proceedings of the IEEE International Workshop on Computer Aided Modeling and Design of Communication Links and Networks(CAMAD)*, Lund, Sweden, June 19-21, 2017, pp. 1-5.

Contribution: This paper was branched out from a larger work aiming at jointly analyzing and optimizing *Idle* DRX, paging and TAU. The model, its verification as well as the paper writing was made by me independently. Emre Yavuz contributed with very valuable information about the mechanisms which was used to improve the paper and descriptions, and also the larger scope paper not covered in this thesis.

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Chapter 1
Introduction

1.1 Motivation

The last decade´s development in the telecommunications sector has been tremendous, from the analogue 1:st Generation (1G) to the IP based 4:th Generation (4G) now widely used. The 4G has brought the Long Term Evolution-Advanced (LTE-A) technology standard, acting as a key part of the 5:th Generation (5G) expected to be rolled out by 2020 [1]. The 5G is bringing improvements on capacity, data rate, latency, QoS and energy usage [2]. The improvement on each area is facilitated by a number of different emerging technologies with huge potentials [3].

The long term investments and widespread use of 4G has pushed the price and performance limits for the products, nonetheless for the mobile devices or User Equipments (UEs). This together with future prospects of LTE-A as a long term technology has attracted the military training sector who long has been relying on proprietary networks. For this sector the key requirements have been long operating range, efficient use of radio resources for short data packets and long battery operating times. Different industrial solutions for this market have led to requirements for interoperability between these systems, and together with the parallel development of the commercial telecommunication networks, new requirements have emerged. These call for lower end-to-end latency and higher bandwidth enabling interoperability between networks as well as new functionalities and services in the training networks, such as voice and video streaming.

The LTE technology is currently evaluated and partly used by the military training sector. However, some key requirements such as meeting traffic deadlines and power saving need to be investigated. In this work, research is performed to fulfill these requirements. A key requirement currently under scrutiny is energy usage in the UEs where the main power saving method is the Discontinuous Reception (DRX) mechanism. The DRX mechanism can be used by UEs in both *Connected* and *Idle* state. A UEs in *Connected* state has an active session and monitors the Physical Downlink Control Channel (PDCCH) for traffic information, whilst in *Idle* state the UE is monitoring for a paging message for transition to *connected* state. DRX enables power saving in UEs by allowing monitoring of the PDCCH only during predetermined intervals and sleeping the remaining time, if no messages arrives. This mechanism is thoroughly investigated in this doctoral thesis to answer current and upcoming questions regarding energy-aware resource handling for LTE-based military training networks, but also applicable to other domains.

1.2 Problem definition

Our research goal is to answer *how to utilize the radio and energy resources in a wireless communication system for a military training application.* It is broken down into three separate research questions:

- How to meet deadlines for heterogeneous real-time traffic and maximize the number of admitted nodes in a centralized wireless communications network?
- How to evaluate standardized DRX power saving mechanism of a LTE radio network?
- How to improve energy-efficiency for the mobile nodes in a LTE-based radio network?

1.3 Methodology

The research questions drawn from the problem formulation, are studied in the State Of The Art (SOTA) literature. For each research question a hypothesis is derived. For testing the hypothesis, functions are identified in the technology being of importance in this aspect. Based on these functions or mechanisms experiments are designed for the tests. The experiments are performed with proposed models, either analytical/numerical or simulation-based, and necessary data is collected. If needed then reiterations are made in any of the different stages (Fig. 1.1). Finally, the hypothesis is tested based on the experiments, whereby the research questions can be answered.

The used analytical/numerical models are deterministic for the real-time protocols, and probabilistic for the energy-aware work. For the real-time protocols improvements are proposed fulfilling requirements of both heterogeneous uplink/downlink traffic and supporting large number of nodes. For the energy-aware work the probabilistic models are validated with simulation tools (mainly Matlab). The DRX mechanism and its different modes and variants are evaluated and DRX parameters tuning including optimization problems are proposed for the power saving and the delay tradeoff.

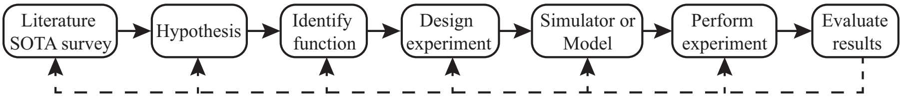

Figure 1.1: Methodology stages

1.4 Contributions

The contributions of this doctoral thesis are:

- A scalability analysis emphasizing on meeting deadlines for heterogeneous real-time traffic **[Paper A]**, and maximizing the number of admitted nodes in a wireless communications network **[Paper B]**.
- A probabilistic model for the DRX mechanism in *Connected* state **[Paper C]**, together with queuing delay analysis **[Paper D]**, optimization enhancements and guidelines on DRX parameter adjustments **[Paper E]**.
- A probabilistic model for the DRX mechanism in *Idle* state **[Paper F]**.

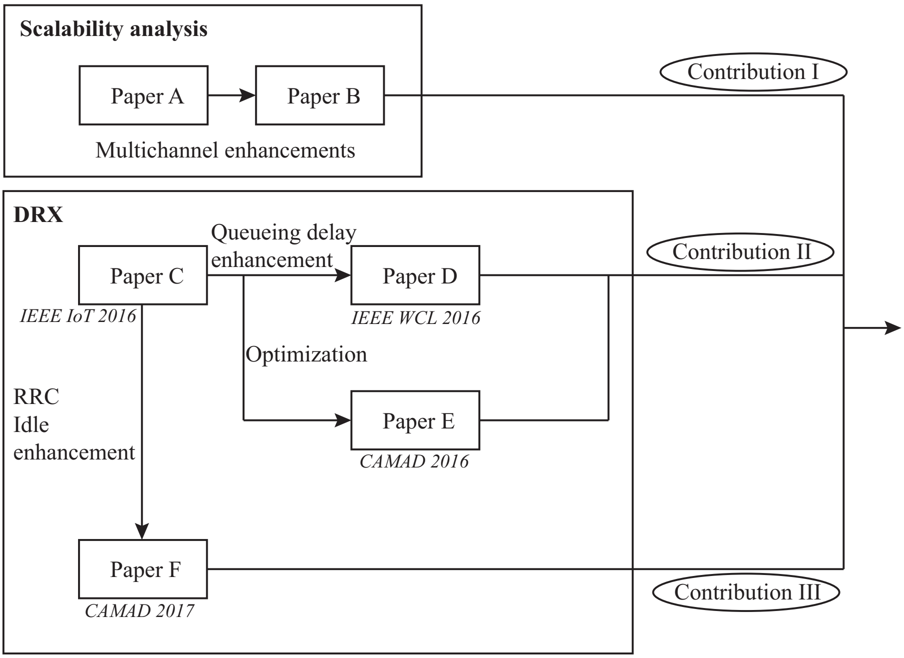

Figure 1.2: Overview of papers

For the single channel scalability analysis, the contribution is an admission control for both uplink and downlink traffic and using two scheduling mechanisms, a control packet based and a data stream scheduler. The data stream scheduler schedules traffic with shorter deadlines than the control packet scheduler can handle. A real-time admission control, fulfilling these features, is a new contribution in the literature. The multichannel scalability analysis provides a heuristic algorithm for allocating mobile nodes to channels in a way that maximizes the number of admitted mobile nodes with different traffic requirements. Admission control with real-time support for multiple channels maximizing number of admitted mobile nodes was not available in the literature making this a novel contribution.

In our first energy-aware work a model is proposed for the complete and reduced DRX mechanisms assuming a traffic model with geometric distribution. This provides a Markovian model with the resolution of one Sub Frame (SF) enabling detailed analysis with a traffic model resembling IoT traffic, i.e low rate and periodic. Previous DRX models are all semi Markovian and our Markovian model is therefore a novel contribution. In addition we assume a DRX process in which arriving traffic during *ON* state do not generate an immediate wake-up, instead the UE has to elapse a sleep cycle. This assumption is allowed by the standard but is rarely used in the literature since it complicates the analysis. However, it provides additional energy saving due to the extra sleep cycle and therefore this variant is also introduced in the literature. The DRX model enables a simple derivation of mean queuing delay. Mean queuing delay is available in the literature but our contribution is novel since it is a simplified way to obtain it from the wake-up delay. Our DRX parameter optimization contribution is novel since it compares results from the complete DRX mechanism to when the reduced DRX mechanism is used and this has not been done in the literature. Additionally, the comparison is done for both periodic and sporadic traffic. Finally, an *Idle* DRX Markovian model is proposed being different to other DRX literature covering *Idle* state, since these are all semi Markovian.

1.5 Thesis organization

The remaining thesis summary is organized as follows. In section 2 the background of military training systems is described. The papers are summarized in section 3. Finally, the conclusions and the future work are given in section 4.

Chapter 2
Background

2.1 Military training systems

The first unofficial military training doctrines are prehistoric but the first official one is documented back to 1778 [4] and was reprinted in [5]. The doctrine covered how to teach military drills, tactics and disciplines in a teach-the-teacher, train-the-trainer manner.

The development of military training systems was enabled by the impact of electronics where cost effective simulators of expensive weapons could be built for realistic training purposes [6]. Connecting these training devices together started to take shape in the 1970s [7] and formed the subarea of live simulation, referring to simulation involving real people operating real systems (preferably in a real environment).

Further development of military training systems formed them into training environments where all members in a military division, referred to as players in the training systems domain, are supervised in a real-time environment. This is done by instrumenting the players with radio modems for data transmission and reception as well as location and activity detection sensors. Moreover, to enable logging of firing data and save cost, laser simulation is used instead of live firing. Wearable devices for a wide area of applications are surveyed in [8].

2.2 Radio network

The prominent technology having increased the system usability has been the radio network. First used to collect data for playback and analysis in After Action Reviews (AARs), it later evolved into providing real-time supervision of the training scenario due to network performance improvements. The network has been designed for low data rate transmission in the Ultra High Frequency (UHF) spectrum. However, it is subject to steadily increasing requirements, lately for multimedia streaming and lower latencies enabling newer functionality and services such as voice, video and improved interoperability between different manufacturers.

Lately LTE/LTE-A has received a great deal of attention from the military training industry due to the worldwide deployment of the standardized technology and the price vs. performance progress of the mobile devices for example the category MTC UEs [9]. Additionally, the future goal for 5G providing IoT and M2M solutions [10] and the inclusion of LTE/LTE-A makes this technology a particularly interesting option for the industry, nonetheless as the main alternative technology besides the proprietary networks.

The military training radio network architecture is typically centralized with a base station, a number of mobile nodes and a network controller responsible for the network administration. Different network components such as base stations and Exercise Control (EXCON) nodes can be interconnected through a wired or wireless backbone network increasing capacity and coverage. Usually, the whole system is scalable and ranges from mobile and man-wearable manpacks to fixed installations covering large training areas with fiber-optical or wireless backhaul networks.

2.3 Mobile nodes

The mobiles nodes must be cost sensitive and provide long battery operating times to fulfill the industry and market requirements. Longer battery operating times minimizes battery logistics being an important requirement for large military divisions. A new mobile radio generation has been developed at Saab Training and Simulation for the proprietary radio network. It is based on Software Defined Radio (SDR) technology which is more flexible and cost effective for reconfiguration both at radio and application level. The transceivers are most usually of half-duplex types.

2.4 The choice of radio system

The interest for LTE/LTE-A based solutions is mainly due to the performance increase, the mobile device price and capability as well as the availability for the deployed LTE/LTE-A telecommunication systems. Against this background, several LTE-based training systems have been successfully evaluated in the industry. Despite this, demands for the proprietary radio networks remains strong, owing to its proved environmental and functional robustness as well as its mobility and simplicity of operation in remote training areas. Another important aspect is the non-line-of-sight nature of the UHF spectrum. Therefore, choices of future radio networks are ambiguous and this research intends to fill the gap by providing answers and solutions for some of the questions.

2.5 Energy-awareness

Green communications targets to minimize the overall resource usage of communications systems [11] through power saving and energy-awareness. Energy-awareness is a key factor in military training communications systems, especially for mobile devices to increase battery operating times. To facilitate this aspect the standardized power management mechanism, DRX [12]-[13] is used. DRX enables power saving in UEs by discontinuous reception in both *Connected* and *Idle* state. In *Idle* state the mechanism saves power by receiving paging messages discontinuously during predefined intervals, and sleeping the remaining time. The paging requests a state change from *Idle* to *Connected* state. Once in *Connected* state, the DRX mechanism monitors the PDCCH only during predefined intervals (*ON* state) to detect if there is indication of awaiting traffic, and if so enters *Active* state. If there is no awaiting traffic then the UE will enter *Sleep* state which can be either of short or long type. When certain conditions of inactivity is met, then the connection is released and UE enters *Idle* state again.

Chapter 3
Summary of papers

The results developed based on the problem definition is summarized below. The works are interlinked as showed in Fig. 1.2 starting with scalability analysis for a single channel case [Paper A] enhanced with multiple channels [Paper B]. Energy-awareness analysis is introduced for LTE/LTE-A using *Connected* state DRX [Paper C], later enhanced with queuing delay metric [Paper D], optimization [Paper E], and *Idle* state DRX [Paper F].

3.1 Paper A

In this paper an admission control using deterministic analysis is used answering *how to meet traffic deadlines with the application specific requirements.*

Our hypothesis states that an admission control can guarantee timely delivery of traffic within a military training network fulfilling the traffic requirements. For this, a real-time analysis based on the processor demand function is used adapted for both uplink and downlink traffic. A single frequency base station with half-duplex mobile nodes is assumed and a split phase protocol using slotted time intervals is then suitable for transmitting both payload and control data on the same radio channel. Two different scheduling mechanisms are implemented. The first is a control packet based mechanism for event based traffic with longer deadlines. The second is a mechanism that schedules data streams and does not need to wait for a control packet turnaround thus enabling scheduling of periodic traffic with shorter deadlines.

It is shown that an admission control with real-time analysis can be used to guarantee both uplink and downlink traffic for the assumed traffic. An upper bound was provided for the number of mobile nodes while guaranteeing the timely delivery of the traffic.

3.2 Paper B

The admission control from [Paper A] is used in this paper to answer *how to maximize the number of admitted mobile nodes with different traffic requirements in the network whilst meeting real-time deadlines.*

The admission control is enhanced for multiple channels and four types of mobile nodes with different traffic are assumed. With this new system model a new admission control is proposed together with a Frequency Allocation Algorithm (FAA) to maximize the number of admitted mobile nodes in the network. The proposed heuristic FAA is evaluated and compared against two well-known heuristic algorithms. The implication of multimedia traffic with different deadlines is also investigated.

It is shown that the proposed algorithm accepts a higher average number of nodes when multimedia traffic deadline is short, i.e. 30-50 ms, but outperformed by the two reference algorithms when the deadline is increased to 60-200 ms. The proposed algorithm performs better since it separates different node types onto separate frequency channels as far as possible, which is advantageous for short multimedia traffic deadlines. On the other hand, the reference algorithms are mixing mobile nodes onto each frequency channel which gives better performance for longer multimedia traffic deadlines.

3.3 Paper C

The DRX power saving mechanism for LTE/LTE-A based networks is evaluated to answer *how to minimize power consumption in mobile devices whilst meeting traffic deadlines.*

The DRX mechanism is modeled with a Markov chain model and two performance measures are derived; the power saving factor defined as the portion of time the device is in sleep; and the wake-up delay defined as the time it takes for the device to wake-up once the first traffic has arrived during the DRX cycle. The model makes a state transition every SF and models all the mechanism states; *active*, *sleep* and *ON*. The traffic model is geometrically distributed with a probability p that traffic arrives in a SF and $1-p$ that traffic does not arrive. The DRX mechanism consists of short and long DRX cycles. When the optional short cycle is disabled it is called the reduced DRX mechanism, and if enabled it is called the complete DRX mechanism. Both mechanisms are modeled separately and verified through means of simulations. Three propositions are proposed describing: 1. how to meet a deadline for a wake-up delay for the complete model, 2. how to meet a deadline for a wake-up delay for the reduced model, and 3. how to maximize the power saving factor.

The DRX mechanism is evaluated with a traffic model for military training traffic to maximize the power saving factor whilst meeting traffic deadlines. In this evaluation the reduced DRX mechanism is used with support of proposition 2 and 3. The complete DRX mechanism is evaluated with a traffic model including multimedia where the packet interarrival time is modeled with simplified bounded Pareto distribution. Since the traffic arrival model for the complete model does not have memoryless properties simulations are used for the evaluation. However, in this case all traffic is queued during DRX.

In this work, novel Markov chain models are proposed for both the reduced and the complete DRX mechanism together with two performance metrics, power saving factor and mean wake-up delay. Propositions and design guidelines are given for DRX parameter tuning to be used in IoT, M2M and particularly military training scenarios.

3.4 Paper D

In [Paper D] the DRX mechanisms are further investigated, to answer *how the delay is affected whilst saving power.*

The DRX mechanism in connected state is considered, and then it is of interest to obtain a measure for the mean queuing and the scheduling delay. To obtain these new metrics the wake-up delay from the connected state DRX model in Paper C is used. With the knowledge of the first instance of traffic during DRX, the accumulated delays are calculated as well as the mean number of packets in queue. With these the mean queuing delay is obtained. However, depending on whether the first traffic arrives in *ON* or *sleep* the DRX mechanism acts differently and therefor the final delay expression consists of two components. These two components are separately calculated and summed for the final mean queuing delay.

In addition to the mean queuing delay a lower bound for the scheduling delay is also obtained resulting in a complete delay analysis for the reduced DRX mechanism.

3.5 Paper E

By using results from previous work, [Paper C] and [Paper D], the optimal performance of the DRX mechanism is investigated to answer *how its different configurations will perform for different traffic types.*

Two optimization problems are defined for the DRX mechanism when periodic and sporadic traffic is used. The first one minimizes mean queuing delay subject to a power saving bound, and the second maximizes power saving factor subject to a mean queuing delay bound. Moreover, two variants of the DRX mechanism is used, the complete and the reduced one. The results from these two configurations will be used to compare the optimal DRX performance using different traffic types.

The results show that the complete DRX mechanism performs well, and provides lower mean queuing delay for both periodic and sporadic traffic. On the other hand, if slightly longer delays can be tolerated the reduced DRX mechanism is able to perform equally well, regarding power efficiency. The advantage is that the optimization is computationally more efficient due to a reduced set of DRX parameters.

3.6 Paper F

In this paper the focus is shifted towards DRX in *Idle* state to answer *how more power can be saved in this state, and which further mechanisms affect the mobile device power saving.*

A model for DRX in *Idle* state is proposed together with the power saving factor metric and a new metric, the reachability delay, defined as the time between the reception of a paging request by the base station and the mobile device. The relation between this DRX mode and other mechanisms affecting mobile device power saving is explored and improvement suggestions are given.

Chapter 4
Conclusions and future work

Conclusions

This doctoral thesis covers resource handling strategies for military training radio networks starting with strategies for admission control resource allocation and continuing with power saving analysis and practical design guidelines. The admission control uses deterministic analysis for a single- and multichannel base station scenario where the latter incorporates a heuristic FAA to maximize average number of accepted nodes. The power saving analysis uses LTE/LTE-A DRX mechanism and a model is proposed for the complete and the reduced DRX mechanism in *connected* mode along with parameter tuning recommendations. The reduced mechanism is enhanced with a mean queuing delay metric. To complete design guidelines, an optimization strategy for *Connected* state DRX is proposed using previous DRX models and metrics. The differences between the reduced and complete DRX mechanism operation when using periodic and sporadic traffic is evaluated, especially for sporadic traffic where long-tail probability distribution, being challenging from a power saving perspective, is used.

Future work

In future work a number of questions can be investigated further towards energy-aware LTE-based military training systems but also applicable to other connected devices domains. One of them is to enhance the *Idle* state DRX mechanism analysis with paging and Tracking Area Update (TAU) analysis. Further aspects to investigate are concerning the rapid growth of the number of connected devices, in particular for LTE/LTE-A and 5G. The expectation of ubiquitous connectivity and increased energy efficiency in both the networks and the devices raise following questions:

- How to further improve operating times for battery operated devices by traffic sensing and DRX parameters optimization and adaptation?

- How to evaluate and improve power saving and cost tradeoff with a holistic view of the network including power saving mechanisms and other functionalities such as paging, TAU, scheduling and device-to-device?
- How to handle the scalability for M2M and IoT networks with minimal change of the technology standards?

Chapter 5
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