Error Control for Radio Frequency Identification

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To Mariana

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Abstract

This work proposes to use Forward Error Correction (FEC) for the tag-to-reader communication in long-range Radio Frequency Identification (RFID) systems, specifically in the widely used EPCglocal Class-1 Generation-2 (EPCc1g2) systems, to overcome some of the limitations that occur at extended communication distances.

In a long-range RFID system, the reader must be able to identify a great number of tagged items in a reliable fashion, and in a limited amount of time. Cluttered propagation paths, difficult channel conditions, and the low power of the backscattered tag signals, make this task difficult. Especially, when the communication distances are high, as for battery-assisted tags, the signal-to-noise ratio at the reader's receiver is low, and the bit-error probability is high. Nevertheless, the widely used standard protocols offer only rudimentary error-control mechanisms. The use of FEC is not yet established in practical systems and has not been widely researched in the context of RFID.

A model was developed, to describe the impact of errors on the duration of the tag identification, and it is subsequently used, to evaluate the use of convolutional codes and their benefits in terms of the improved identification time, related to the tag-reader distance. For a chosen code, it was shown that the range of the system can be extended by approximately 4 m without increasing the identification time. Furthermore, the application of an iterative decoder architecture is presented that is used to decode the concatenated code, which is formed by the proposed FEC code and the standard EPCc1g2 baseband codes. An improvement of the coding gain of up to 2.8 dB could be shown in simulations, comparing the iterative decoder to a non-iterative one. Additionally, the convergence behavior of the decoder is analyzed and its limitations are discussed.

Since a great number of RFID systems have already been deployed worldwide, standards and standard compatibility should be a great concern, when

proposing extensions for an existing system. It is shown in this work, how a standard EPCc1g2 system may be improved, by using combining at the reader to minimize the number of retransmissions that are caused by frame-errors. Furthermore, it is shown how the standard may be extended with Hybrid Automatic Repeat Request (HARQ) functionality, without losing backward compatibility. Simulations of the identification time as well as the system's throughput show significant improvements when using the proposed schemes.

Finally, tag collisions are another concern in EPCc1g2 systems. It is investigated whether the use FEC can increase the frequency of captures: i.e., recoverable tag collisions. To this end, a capture model is proposed, and the relations for some important channel models are derived. This capture model is then used to evaluate the throughput without and with FEC coding. An increased capture probability can be demonstrated when using FEC, however, the improvement of the system's throughput is not very pronounced, when only regarding the influence of captures.

Zusammenfassung

Die vorliegende Arbeit untersucht die Eignung von Vorwärtsfehlerkorrekturverfahren (FEC) zur Verbesserung der Kommunikation zwischen Transpondern und Lesegerät in einem long-range Radio Frequency Identification (RFID) System. Der Fokus liegt dabei auf den EPCglocal Class-1 Generation-2 (EPCc1g2) Systemen.

Das Lesegerät in einem long-range RFID System muss in der Lage sein eine große Anzahl markierter (getaggter) Gegenstände in einer limitierten Zeit zuverlässig zu identifizieren. Die in diesen Systemen vorherrschenden Ausbreitungsbedingungen, stark gestörte Übertragungskanäle und die geringe Leistung der empfangenen Transpondersignale stehen dieser Aufgabe entgegen. Besonders wenn die Kommunikationsentfernungen, wie bei semi-passiven Transpondern, groß sind, ist der Signal-Rauschabstand der Tagsignale niedrig und die Fehlerwahrscheinlichkeit hoch. Obwohl diese Probleme hinreichend bekannt sind, gibt es in den zurzeit standardisierten Protokollen nur sehr einfache Fehlerschutzmechanismen. FEC wird in der Praxis noch nicht eingesetzt und ihr Einsatz in RFID Systemen ist noch nicht ausreichend erforscht.

In dieser Arbeit wird zunächst ein Modell beschrieben, welches den Einfluss von Übertragungsfehlern auf die Identifikationszeit der Transponder beschreibt. Anhand dieses Modells wird der Einsatz von FEC evaluiert und es werden die Auswirkungen auf die maximale Lesereichweite des Systems aufgezeigt. Für einen ausgewählten Code konnte gezeigt werden, dass sich so die Reichweite des System um 4 m erhöhen lässt, ohne dass dabei die Identifikationszeit steigt. Weiter wird ein iterativer Decoder vorgestellt der dazu verwendet werden kann, den verketteten Code zu decodieren, welcher sich aus dem vorgeschlagenen Faltungscode und den standardisierten EPCc1g2 Leitungscodes ergibt. Dabei konnte in Simulationen eine Verbesserung des Codiergewinns um bis zu 2.8 dB, beim Vergleich des iterativen mit einem nicht-iterativen Decoder, erzielt werden. Zudem wird das Konvergenzverhalten des Decoders untersucht.

Da sich weltweit bereits viele RFID Systeme im Einsatz befinden, sollten mögliche Erweiterungen stets mit Hinblick auf deren Kompatibilität zu den heutigen Standards entworfen werden. Es wird in dieser Arbeit gezeigt, wie sich die bereits in Gebrauch befindlichen EPCc1g2 Systeme mit Combining-Verfahren erweitern lassen, um die Anzahl von Wiederholungen gestörter Pakete zu minimieren. Weiter wird aufgezeigt, wie sich der existierende Standard um Hybrid Automatic Repeat Request (HARQ) Funktionalität erweitern lässt, ohne die Kompatibilität zu älteren Standardsystemen einzubüßen. In Simulationen konnte für die vorgeschlagenen Erweiterungen eine signifikante Reduktion der Identifikationszeit bzw. eine Erhöhug des Datendurchsatzes demonstriert werden.

Ein letzter Aspekt sind die in EPCc1g2 unvermeidlichen Kollisionen von Transponderantworten. Es wird untersucht, ob FEC dazu beitragen kann die Häufigkeit von *Captures*, d. h. die spontane Auflösung von Kollisionen, zu erhöhen. Dazu wurde ein Capture-Modell entwickelt und die Zusammenhänge für einige wichtige Kanalmodelle hergeleitet. Anhand dieses Modells wird schließlich untersucht, ob der Einsatz von FEC den Durchsatz des Systems steigern kann. Dabei ist beim Einsatz von FEC zwar eine Erhöhung der Capturewahrscheinlichkeit nachweisbar, jedoch ergibt sich daraus nur eine geringe Verbesserung des Durchsatzes im System.

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Acronyms

ALOHA A statistical multiplexing and media access control scheme developed from 1968 on at the University of Hawaii.

APP A Posteriori Probability.

ARQ Automatic Repeat Request.

ASK Amplitude Shift Keying.

auto-id Automatic Identification.

AWGN Additive White Gaussian Noise.

BAP Battery-assisted passive tags.

BCH Bose Chaudhuri Hocquenghem (code), named after the inventors.

BER Bit-Error Rate.

BNetzA Bundesnetzagentur.

BPSK Binary Phase Shift Keying.

BSC Binary Symmetric Channel.

CC Chase Combining.

CDF Cumulative Distribution Function.

CRC Cyclic Redundancy Check.

CW Continuous Wave, referrers to an unmodulated carrier signal.

DBC Differential Phase Shift Keying.

DPSK Differential Phase Shift Keying.

DTMC Discrete Time Markov Chain.

EEPROM Electrically Erasable Programmable Read-Only Memory.

EPCc1g2 EPCglocal Class-1 Generation-2.

ERP Effective Radiated Power.

EXIT chart Extrinsic Information Transfer chart.

FCC Federal Communications Commission.

FEC Forward Error Correction.

FM Frequency Modulation.

FSA Framed Slotted ALOHA.

FSM Finite-State Machine.

HARQ Hybrid Automatic Repeat Request.

HF High Frequncy, frequency range from 3 MHz to 30 MHz.

IC Integrated Circuit.

IR Incremental Redundancy.

ISO International Organization for Standardization.

LBT Listen Before Talk.

LF Low Frequncy, frequency range from 30 kHz to 300 kHz.

LLR Log-Likelihood Ratio.

MAC Media Access Control.

MIMO Multiple input, multiple output.

MLSE Maximum likelihood sequence estimation.

MR combining Maximum Ratio combining.

N-LOS non line-of-sight.

OFD Optimum Free Distance (code). A convolutional code with the maximum free disctance for a given constraint length.

PDF Probability Density Function.

PIE Pulse-Interval Encoding.

PMF Probability Mass Function.

PSK Phase Shift Keying.

R-to-T reader to tag.

RADAR Radio detection and ranging.

RCPC Rate Compatible Punctured Convolutional.

RCS Radar Cross-Section.

RF Radio Frequency.

RFID Radio Frequency Identification.

RSC Recursive Systematic Convolutional.

SAW Surface Acoustic Wave.

SISO Soft Input Soft Output.

SNR Signal-to-Noise Ratio.

T-to-R tag to reader.

UHF Ultra High Frequncy, frequency range from 300 MHz to 3000 MHz.

VLSI Very-Lage-Scale Integration.

WGN White Gaussian Noise.

Nomenclature

λ	Wavelength.
ν	Memory of a convolutional coder.
$P_{K,i}\left(m\right)$	Probability of finding m slots occupied by one tag.
$P_{K,i}\left(m,R\right)$	Probability of finding m slots occupied by R tags.
ρ	Complex reflection coefficient.
σ	Radar cross-section of the tag.
a	Maximum number of retransmissions.
A_r	Random variable describing the real part of the channel coefficient H_r.
d	The distance between a tag and the reader.
d_f	Free distance of a convolutional code.
d_h	Hamming distance of a block code.
$E\left[\cdot\right]$	Expected value of a ramdom variable
E_b	Bit energy.
E_s	Symbol energy.
$F_A(a)$	Cumulative distribution function of the random variable A.
$f_A(a)$	Probability density function of the random variable A.
G_r, G_t	Gain of the reader antenna and the tag antenna.
$\mathbf{H}$	Random vector of independent channel coefficients $(H_1, \ldots, H_r)$.

h_f, h_b Complex channel coefficient of the backward and forward link in a backscatter system

H_r Random variable describing the channel coefficient of the r^{th} tag.

K Number of slots in an inventory round.

K_α Modified Bessel function of the second kind

L_p, l_p Path-loss and path-loss in dB

L_s, l_s Free-space path loss and Free-space path loss in dB

N Size of the tag population.

N_0 Noise (power) spectral density.

$\mathbf{P}$ Transition matrix of a Discrete Time Markov Chain

p_b Bit-error probability.

$P_c(R)$ Capture probability in a slot with R tags

p_f Frame-error probability.

$p_{i,j}$ Transition probabilities from state s_i to s_j of a discrete-time Markov chain.

p_s Slot-error probability: The probability that any of the frames in a slot of the inventory round contains errors.

p_{sym} Symbol-error probability.

P_{th}, p_{th} Turn-on or threshold power of a tag in W or dBm.

R Occupancy number of a slot in an inventory round.

$\mathcal{S}$ Set of states of a Discrete Time Markov Chain

t Error-correction capability of a block code.

T, T_c Frame-local throughput without and with consideration of the capture effect.