
Authentication in Insecure Environments

Sebastian Pape

Authentication in Insecure Environments

Using Visual Cryptography and Non-
Transferable Credentials in Practise

Dr. Sebastian Pape
Dortmund, Germany

Doctoral thesis at the University of Kassel, Department Electrical Engineering and Computer Science, defended on September 2nd, 2013, submitted with the title “The Challenge of Authentication in Insecure Environments” by Sebastian Pape

ISBN 978-3-658-07115-8

ISBN 978-3-658-07116-5 (eBook)

DOI 10.1007/978-3-658-07116-5

The Deutsche Nationalbibliothek lists this publication in the Deutsche Nationalbibliografie; detailed bibliographic data are available in the Internet at <http://dnb.d-nb.de>.

Library of Congress Control Number: 2014948456

Springer Vieweg

© Springer Fachmedien Wiesbaden 2014

This work is subject to copyright. All rights are reserved by the Publisher, whether the whole or part of the material is concerned, specifically the rights of translation, reprinting, reuse of illustrations, recitation, broadcasting, reproduction on microfilms or in any other physical way, and transmission or information storage and retrieval, electronic adaptation, computer software, or by similar or dissimilar methodology now known or hereafter developed. Exempted from this legal reservation are brief excerpts in connection with reviews or scholarly analysis or material supplied specifically for the purpose of being entered and executed on a computer system, for exclusive use by the purchaser of the work. Duplication of this publication or parts thereof is permitted only under the provisions of the Copyright Law of the Publisher's location, in its current version, and permission for use must always be obtained from Springer. Permissions for use may be obtained through RightsLink at the Copyright Clearance Center. Violations are liable to prosecution under the respective Copyright Law. The use of general descriptive names, registered names, trademarks, service marks, etc. in this publication does not imply, even in the absence of a specific statement, that such names are exempt from the relevant protective laws and regulations and therefore free for general use. While the advice and information in this book are believed to be true and accurate at the date of publication, neither the authors nor the editors nor the publisher can accept any legal responsibility for any errors or omissions that may be made. The publisher makes no warranty, express or implied, with respect to the material contained herein.

Printed on acid-free paper

Springer Vieweg is a brand of Springer DE.

Springer DE is part of Springer Science+Business Media.

www.springer-vieweg.de

For my parents

Preface

For scientific research it is essential to have interested conversational partners who come up with helpful suggestions, references and especially criticism. At this point, I like to thank them for their kind support when writing this thesis.

I particularly owe thanks to my supervisor Prof. Dr. Lutz Wegner, who in the first place made this work possible, supported me at any time with thematically and scientific advice and also untiringly encouraged me regarding all other aspects.

I thank Prof. Dr. Jan Jürjens for enabling me to finish my work at his chair, for his active support and for appraising this work.

Furthermore, I appreciate very constructive and helpful discussions about the application of anonymous credentials with Prof. Dr. Andreas Pfitzmann. I am also very thankful to Dipl.-Inf. Marit Hansen for her valuable advice, which facilitated entering the topic of privacy-enhancing technologies.

I also like to thank Dr. Sebastian Gajek and M.Sc. Denise Doberitz for fruitful discussions on visual cryptography which had a large influence that this subject was examined to this extent.

I extend my thanks to all to my former colleagues at Kassel University as well as to my current colleagues at Dortmund Technical University and the Fraunhofer Institute for Software and Systems Engineering. In particular, my thanks go to Dipl.-Ing. Michael Möller for his active support and to Dipl.-Inf. Christian Wessel for numerous helpful comments and suggestions.

I am grateful to Bruce Schneier and Kim Cameron for the permission to include photographs from their blogs in this work. I also like to thank the anonymous reviewers whose comments helped to improve the papers which were published previously and which this work is based on.

I express my sincere gratitude to all the persons mentioned here. Nevertheless, without saying all possible errors and inaccuracies go completely to my account. I am grateful for further suggestions or comments on this work.

Dortmund

Sebastian Pape

Contents

List of Figures	XIII
List of Tables	XV
1 Introduction	1
1.1 Authentication in Insecure Environments	1
1.2 Overview	4
I Preliminaries	7
2 Mathematical and Cryptographic Foundation	9
2.1 Preliminaries and Notation	9
2.1.1 Functions and Algorithms	9
2.1.2 Basic Group Theory	18
2.2 Encryption Schemes	22
2.2.1 Notions of Security	27
2.2.2 Passive Attacks	28
2.2.3 Security Models	35
2.2.4 Active Attacks	45
2.2.5 Practical Security	53
2.3 Cryptographic Hardness Assumptions	58
2.3.1 The Factoring and RSA Assumption	58
2.3.2 The Discrete Logarithm and Diffie-Hellman Assumptions	61
2.4 Hash Functions and Digital Signature Schemes	67
2.4.1 Hash Functions	67
2.4.2 Digital Signature Schemes	68
2.4.3 Blind Signatures	72

II	Human Decipherable Encryption Schemes	79
3	Introduction, Scenario, and Related Work	81
3.1	Background and Purpose	81
3.2	Overview	84
3.3	Scenarios	85
3.4	Related Work	85
4	Human Decipherable Encryption Scheme	87
4.1	Notation and Terminology	87
4.1.1	Messages, Codings, Ciphertexts and Keys	87
4.1.2	Unicity Distance	89
4.1.3	Encodings and Decodings	95
4.1.4	Human Decipherable Encryption Scheme	103
4.1.5	XOR, EQV and Hamming Functions	117
4.2	Visual Cryptography	119
4.2.1	Pixel-based Visual Cryptography	120
4.2.2	Segment-based Visual Cryptography	124
4.2.3	Applications of Visual Cryptography	127
4.2.4	Using Key-Transparencies Multiple Times	130
5	Human Decipherable Encryption Schemes Based on Dice Codings	135
5.1	Dice Codings	135
5.1.1	Underlying Spaces and Parameters	135
5.1.2	Coding Scheme	137
5.2	Basic Version	139
5.2.1	EQV Encryption Scheme	139
5.2.2	Basic Human Decipherable Encryption Scheme	141
5.3	Security Analysis of the Basic Version	145
5.3.1	Ciphertext-Only Attacks Without Side Information	146
5.3.2	Ciphertext-Only Attacks With Side Information	149
5.3.3	Security Models	167
5.4	Dice Codings with Noise	174
5.4.1	Changes in Underlying Spaces and Parameters	174
5.4.2	EQV Encryption Scheme with Noise	175
5.4.3	Human Decipherable Encryption Scheme with Noise	178
5.5	Security Analysis of Dice Codings with Noise	183
5.5.1	Ciphertext-Only Attacks Without Side Information	184
5.5.2	Ciphertext-Only Attacks With Side Information	185
5.5.3	Security Models	192

6	Conclusion and Future Work	197
6.1	Summary and Conclusion	197
6.2	Future Work	198
6.2.1	Addressing Other Senses than Sight	198
6.2.2	Security Assumptions and Models	201
6.2.3	Methods to Improve Reusing the Key-Transparencies	202
III	Non-Transferable Anonymous Credentials	207
7	Introduction, Scenario, and Related Work	209
7.1	Background and Purpose	209
7.2	Overview	210
7.3	Scenarios	210
7.4	Related Work	211
8	Privacy and Data Security	213
8.1	Notions and Terms of Privacy	213
8.1.1	Anonymity, Pseudonymity, Unlinkability, Untraceability	213
8.1.2	Trust Levels Regarding Privacy	214
8.2	Anonymous Credentials	215
8.2.1	Properties of Anonymous Credentials	216
8.2.2	Zero-Knowledge Proofs	217
8.2.3	Wallet-With-Observer Architecture	219
8.3	Smartcards and Biometrics	220
8.3.1	Smartcards	220
8.3.2	Biometrics	221
9	Analysis of Non-Transferable Anonymous Credentials	229
9.1	Approaches Aiming at Non-Transferability	229
9.1.1	Embedding Valuable Secrets	229
9.1.2	Biometrically Enforced Non-Transferability	230
9.1.3	Consideration of Other Approaches	231
9.1.4	Security Issues	232
9.1.5	Limiting the Consequences of Security Breaches	242
9.2	Templateless Biometric-Enforced Non-Transferability	244
9.2.1	Adapting Schemes to Work without Templates	246
9.2.2	Comparison of Approaches' Security	249

10 Conclusion and Future Work	253
10.1 Summary and Conclusion	253
10.2 Future Work	254
 IV Outlook and Appendix	 257
11 Summary, Conclusion and Outlook	259
11.1 Summary	259
11.2 Conclusion	260
11.3 Outlook	261
 Example of Pixel-based Visual Cryptography in Detail	 265
 Auxiliary Tables and Proofs	 271
 Source Code Listings	 281
 Bibliography	 307
 List of Symbols and Abberviations	 349
 Index of Keywords	 353
 Index of Names	 359

List of Figures

2.1	Relations between Security Models for Asymmetric Encryption .	38
2.2	Visualisation of Game-Based IND-atk Security Models	39
2.3	Relations between Securitymodels for Symmetric Encryption . .	45
2.4	Setup of Active Attacks on the Communication Channel	45
2.5	Protocol Flow of a Man-in-the-Middle Attack	51
2.6	Key pads	56
2.7	Diffie-Hellman Key Exchange Protocol	64
2.8	Blind Signature Scheme	75
2.9	Chaum's Blind Signature Protocol	77
3.1	Example for Visual Cryptography	83
3.2	Transparencies for Visual Cryptography	84
4.1	Relations of Encoding and Encryption Functions' (Co-)Domains .	87
4.2	Representation of Cipher	91
4.3	Seven-Segment Display: Digits	101
4.4	Seven-Segment Display: Notation of Segments	101
4.5	Example of Pixel-Based Visual Cryptography	120
4.6	Visual Forms of Shares with 4 Subpixels	121
4.7	Visual Forms of Shares Represented by Rotated Half Circles . . .	122
4.8	Shares of a 4 out of 4 Visual Secret Sharing Problem	124
4.9	Shares Usable for Steganography in Visual Cryptography	125
4.10	Principle of Visual Cryptography applied to a 7-Segment Display	126
4.11	Application of Visual Cryptography	129
4.12	Reusing Transparencies in Pixel-Based Visual Cryptography . . .	131
4.13	Segment-Based Visual Cryptography: Sample Encryptions	132
4.14	Segment-Based Visual Cryptography: Possible Keys	133
4.15	Closed Subgroup in Segment-Based Visual Cryptography	134
5.1	Dice Codings: Sample Encodings	136
5.2	Sample Visualisations of $\mathcal{HE}_{\text{DICE}}$	143
5.3	Representation of Possible Keys with a Binary Tree	166

5.4	Sample Visualisation of the Ext Function	176
5.5	Sample Visualisations of the Noise Function	177
5.6	Sample Visualisations of the Noise ⁻¹ Function	179
5.7	Sample Visualisation of $\mathcal{HE}_{\text{DICE}}^*$	181
6.1	'University of Kassel' Written in Grade 2 Braille	199
6.2	Refreshable Braille Display	200
6.3	Rotating $\mathcal{HE}_{\text{DICE}}$ -keys	203
8.1	FEIGE-FIAT-SHAMIR Identification Scheme	219
8.2	Fingerprint Charade	223
9.1	Points of Attacking a Biometric System	233
9.2	Sharing a Credential via Radio Transmission	238
9.3	Combining Biometrics with Anonymous Credentials	245
9.4	Modified FEIGE-FIAT-SHAMIR Identification Scheme	248
1	Example of Pixel-based Visual Cryptography: Original Picture . .	266
2	Example of Pixel-based Visual Cryptography: Transparency 1 . .	267
3	Example of Pixel-based Visual Cryptography: Transparency 2 . .	268
4	Example of Pixel-based Visual Cryptography: Overlay	269

List of Tables

2.1	Syverson's Taxonomy of Replay Attacks	53
4.1	International Morse Code (letters)	97
4.2	Example of Hexadecimal Encodings for a 7-Segment Display . .	101
4.3	XOR and Identity Truth Tables	118
4.4	Contingency and Evaluation Table for the Overlay of Two Pixel-Based Transparencies in Visual Cryptography	121
4.5	Contingency and Evaluation Table for the Overlay of Two Segment-Based Transparencies in Visual Cryptography	127
4.6	7-Segment-Display XOR Contingency Table	134
5.1	Dice Codings: Numbers of possible Encodings	136
5.2	Contingency Table for the Encryption with EQV	140
5.3	Contingency and Evaluation Table for the Decryption with EQV .	141
5.4	Possible Numbers of Different Dots for Dice Codings' Ciphertexts	148
5.5	Probabilities of Uniformly Distributed Characters' Dice Codings .	150
5.6	Evaluation of $P(\#0* = 2; 3 N)$'s summands for selected N, N_{1*} .	156
5.7	Evaluation of $P(\#0* = 2; 2 N)$'s summands for selected N, N_{1*} .	158
5.8	Probabilities to Attack Single Characters Encrypted with $\mathcal{HE}_{\text{DICE}}$	159
5.9	Expected Value and Standard Deviation of Distributions	160
5.10	Probabilities of Binomial Distributed Characters' Dice Codings .	161
5.11	Number of Needed Ciphertexts to Attack Pairs of Ciphertexts . .	163
5.12	Number of Needed Ciphertexts to Attack Complete Key pads . . .	167
5.13	Contingency and Evaluation Table for the Decryption with EQV*	180
5.14	Probabilities of Hamming Differences of $\mathcal{HE}_{\text{DICE}}^*$ Encrypted Uniformly Distributed Characters	188
5.15	Conditional Probabilities of Hamming Differences of $\mathcal{HE}_{\text{DICE}}^*$ Encrypted Uniformly Distributed Characters	190
5.16	Probabilities of Determining the Positions of Noise	193
6.1	Contingency Table for Audible Encryption with EQV	201
6.2	Composition of Keys for $\mathcal{HE}_{\text{DICE}}^*$	204

9.1	Attributes of Different Non-Transferability Approaches	241
9.2	Relevant Risks Enforcing Biometric Authentication	252
1	Pairs of Dice Codings for a Given Number of Different Dots . . .	274
2	Upper Bounds of Probabilities for k Matching Ciphertexts	275
3	Probabilities that N_{i^*} Ciphertexts of i^* Occur	276
4	Probabilities that N_{1^*} Ciphertexts of 1^* Occur with $N_{0^*} = 2$. . .	277
5	Probabilities that N_{1^*} Ciphertexts of 1^* Occur with $N_{0^*} = 3$. . .	278
6	Evaluation of $P(\#0^* = 3; 3 N)$'s summands for selected N, N_{1^*} .	279
7	Needed CPU Time to Attack Complete Keypads	280