MINEX II

Performance of Fingerprint Match-on-Card Algorithms
Phase IV Report

NIST Interagency Report 7477

(Revision II)

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Executive Summary

The MINEX II trials have been conducted to evaluate the accuracy and speed of MATCH-ON-CARD verification algorithms. These run on ISO/IEC 7816 smartcards. They compare reference and verification data conformant to the ISO/IEC 19794-2 COMPACT CARD fingerprint minutia standard. The test is an assessment of the core viability of matching fingerprints (i.e. the de facto leading compact biometric data element) on personal identity credentials based on the industry-standard smart cards. The results are relevant to users of minutia templates as additional authentication factor.

This document is the third publication of MINEX II results. The prior two releases[1] were published on February 29, 2008 and on May 21, 2009. The number of MATCH-ON-CARD implementations has increased from 12 in 2008, via an additional 7 in 2009, to 17 in 2010. The number of card-provider algorithm-provider teams was 5 in 2008, 4 in 2009, and 12 in 2010.

The significant results of this report support the proposed inclusion of MATCH-ON-CARD in the U. S. Government's PIV program. Initial requirements appear in the recently drafted Federal Information Processing Standard (FIPS) 201-2[2], and NIST is now developing MOC specifications for PIV.

- MATCH-ON-CARD(MOC) implementations from five providers would meet the minimum error rate interoperability specifications of the United States' Government's PIV program for MATCH-OFF-CARD implementations. Dedicated MATCH-ON-CARD specifications for PIV are under development. The increase in interoperable accuracy and in the number of PIV-capable commercial providers (from two in 2009 to five in 2010) represents a maturation of the marketplace of standards-compliant products. Sec. 6
- PIV compliance, and the success of a MOC deployment, depend on more than the on-card matching algorithm. The minutia detection algorithm used to prepare the card's reference template, and authentication templates is critical also, such that the selection of the template generator is now more influential on error rates than is the matching algorithm itself. Good minutia detection algorithms reliably find the same minutiae in two captured images of the same finger. Poor generators have caused several MOC implementations tested here and in prior MINEX II phases to narrowly miss PIV compliance. This warrants further development, standardization, test and calibration work. Sec. 4.3
- MATCH-ON-CARD remains a technically difficult task, however: Algorithms from two other providers miss the PIV requirements despite those providers having PIV-compliant MATCH-OFF-CARD implementations. This shows that the porting of algorithms running on general purpose computers to smart cards is a non-trivial task. The number of providers of off-card minutiae matching algorithms greatly exceeds that for on-card. Sec. 6
- MOC deployments should adopt template generators that report minutia quality values, such as those submitted to MINEX II. Reliable quality values are vital in the preparation of the compact-format templates sent to the card, particularly from noisy images. Sec. 6
- Biometric providers usually do not publish operating thresholds needed to achieve target false match rates(FMRs). Providers establish the threshold value via internal calibration on proprietary databases. This report for the first time includes FMR threshold calibration information derived from authentication of images from nearly 125000 individuals. In addition the calibration is based on fingerprint minutia from more than 20 minutiae detection algorithms. This supports MOC use in federated applications where template generators from from multiple providers are in use. Sec. 7
- The two fastest implementations, from Precise Biometrics and ID3, execute 50% of genuine ISO/IEC 7816 VERIFY commands in less than 0.1 seconds and almost all comparisons within 0.25 seconds. Additionally a Morpho algorithm executes in 0.15 seconds. These times are so fast as to be negligible and imperceptible parts of an end-to-end human authentication attempt. These algorithms meet the PIV accuracy specifications. Sec. 5

[1] The 2008 and 2009 reports are archived at *http://www.nist.gov/customcf/get_pdf.cfm?pub_id=902634* and *http://www.nist.gov/customcf/get_pdf.cfm?pub_id=150676*.
[2] See http://csrc.nist.gov/publications/pubsfips.html

- ▷ Some providers of MATCH-ON-CARD implementations have improved both accuracy and speed over the three years spanned by the three MINEX II evaluations. A single Morpho algorithm submitted in 2007 and 2010 is now more than three times faster due solely to improvements in the card. A Precise Biometrics algorithm implemented runs approximately 15 times more quickly on one card than another. MINEX II did not quantify card cost, so whether this affords a cost-speed tradeoff is not known. Sec. 8
- ▷ Fingerprint vendors expend considerable money and engineering resources to improving fingerprint algorithms. This activity has produced faster and more accurate MATCH-ON-CARD implementations, as measured by MINEX II. However, these accuracy improvements are smaller by an order of magnitude than the accuracy variation caused by the presence of poorly performing minutia template generators. While providers reasonably focus their attention toward internal research and development to differentiate their product, the marketplace may be supported by increasing efforts to improve interoperabiliy via improving ISO/IEC 19794-2, associated performance tests and calibration efforts, and development of the ISO/IEC 29109-2 amendment on semantic conformance. Sec. 6
- ▷ Over its three year duration, MINEX II has attained unprecedented transparency in its execution: the evaluation plan was published during its development with industry, and MATCH-ON-CARD providers were able to implement a single fixed open ISO/IEC 7816 based interface. Further NIST released version-controlled open-source software for both conformance and conversion of INCITS 378 and ISO/IEC 19794-2 COMPACT CARD templates[a], and for invocation the ISO/IEC 7816 MATCH-ON-CARD operations. The testing protocol has now been standardized as ISO/IEC 19795-7:2011 *Testing of on-card biometric comparison algorithms*. Ann. A

[a]These standards are available from http://webstore.ansi.org.

Caveats

Biometric test reports are relevant only within a particular context, and therefore a caveats apply to the quantitative results and conclusions of this report. Particularly MINEX II did not evaluate interface standards, secure transmission protocols, nor card or algorithm vulnerabilities. In addition it did not consider fingerprint sensors and interoperability between them, nor modalities beyond fingerprints[4]. The following points should influence policy, planning and operational decisions. Further a complete discussion of the advantages and limitations of MATCH-ON-CARD is beyond the scope of this report.

1. The absolute error rates quoted here were measured over a very large fixed corpus of operational fingerprint images. However, error rates observed in real-world applications are strongly dependent on a number of factors legitimately not reflected in the experimental design of MINEX II . Among these are:
   - ▷ Environment - For instance, low humidity is associated with higher false rejection;
   - ▷ Number of verification attempts - More attempts lead to lower false rejection, and higher false acceptance;
   - ▷ Number of presentations allowed, and the decision policy - several images improves accuracy;
   - ▷ Number of fingers used, and the fusion policy - images from two or more fingers improves accuracy;
   - ▷ Demographics - Younger adult populations are widely considered to be easier to match;
   - ▷ Habituation - Users who regularly interact with a system experience lower rejection rates;
   - ▷ The sensor, and the enrollment policy - The application of quantitative quality criteria, e.g. in an auto-capture loop, improves error rates;
   - ▷ The data format in use - Proprietary templates generally offer superior error rates to standardized formats[8], but are non-interoperable. Proprietary extensions to standard templates are similarly non-interoperable unless executable code for each vendor's extensions is built into the reader or read from the card.
2. With respect to MOC specifically, the accuracy and speed of operational verification transactions will generally depend on a number of factors, including the following.
   - ▷ The operational card stock in use.
   - ▷ The number of templates stored on the card.
   - ▷ The number of fingers presented.
   - ▷ The quality of the enrollment procedure, particularly whether a verification was done at time of card issuance.
   - ▷ The communications channel and interface.
   - ▷ The cryptographic operations needed to secure the channel and to authenticate the card and data elements (but see SBMOC in section 1.3).

In addition, the template generation and matching algorithms are strongly influential on error rates. To the extent that MINEX II measured the accuracy of leading industrial and academic algorithms (i.e. only partially), these aspects are documented here. Thus this MINEX trial addresses the core algorithmic capability of a MOC implementation. The results:

- ▷ support qualification processes (e.g. PIV),
- ▷ have relevance operationally (matching accuracy and speed are strongly *influential* components of a system),
- ▷ are not sufficient for prediction of fielded performance.

Disclaimer

Specific hardware and software products identified in this report were used in order to perform the evaluations described in this document. In no case does identification of any commercial product, trade name, or vendor, imply recommendation or endorsement by the National Institute of Standards and Technology, nor does it imply that the products and equipment identified are necessarily the best available for the purpose.

Release Notes

- This revision of this document still uses the term MATCH-ON-CARD instead of the term ON-CARD COMPARISON which has been adopted by the Working Group 11 of ISO/IEC SC 17, and Working Group 5 of ISO/IEC SC 37. The older term, MATCH-ON-CARD, is deprecated in those forums.
- The MINEX II evaluation was conducted in accordance with the MINEX II Specification which has been released as a separate NIST Interagency Report, NISTIR 7485[9]. The plan was developed by NIST in consultation with members of the fingerprint and smart card industries. The document was drafted in April 2007, circulated for public comment, and finalized on August 15, 2007. The NISTIR version adds only a note on context, a coversheet, and acknowledgments to it. It is cited herein, and because it is a suitable protocol for other organizations wishing to evaluate MATCH-ON-CARD implementations.
- In late 2008 the MINEX II Specification was submitted toward the ISO/IEC 19795 - Biometric Performance Testing and Reporting - Part 7 standard on testing of on-card biometric comparison algorithms. This was developed in ISO/IEC JTC 1's Subcommittee 37 Working Group 5, and completed in 2010. Publication is pending[a].
- Thoughout this report the implementations are identified as MX2-IV-x, with $x \in \{A - Q\}$. This association supports automated administration of the test, and conserves space in the tables of this report. The letter codes were assigned in approximate order of receipt of the implementation and its passing of subsequent validation and conformance trials. For reference, the letters are associated with the providers' names in a running footnote.
- Letters MX2A → MX2M denote implementations tested in the period 2007 to 2008. Letters MX2N → MX2T refer to those tested from late 2008 to 2009. See Table 1.
- Much of the tabulated content in this report was produced automatically. This involved the use of scripting tools to generate directly typesettable LaTeX content. This improves timeliness, flexibility, maintainability, and reduces transcription errors.
- Correspondence regarding this report should be directed to MINEXII@NIST.GOV.

[a] See http://www.iso.org/iso/catalogue_detail.htm?csnumber=53059.

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Participation

With the primary MINEX II objective to ascertain MATCH-ON-CARD capability by measuring fingerprint algorithm accuracy in the intended environment (i.e. the card), the test allowed card vendors to team with several fingerprint algorithm vendors, and vice versa. This policy reflected the notion that if accuracy can be traded against speed, then a fingerprint supplier's technology may demonstrate improved accuracy when implemented on a more capable card. NIST therefore required identification of both the card and fingerprint technology suppliers, and these are presented in Table 1. Note Participants were encouraged, but not required, to supply an INCITS 378 fingerprint minutia template generator. One elected to do so in Phases I and II, two did so in Phase III, five did so in Phase IV.

Card Vendor	Fingerprint Matcher Vendor	Card Vendor ID	Fingerprint Vendor ID	NIST IDs	Phases I - IV	
					Generator	Matcher
TecSec	Precise Biometrics	00990100	000B0100	MX2A		I
TecSec	Precise Biometrics	00990101	000B0101	MX2B		I
Internet Risk Management	Neurotechnologija	00312001	00312001	MX2C	I	I
Sagem Morpho	Sagem Morpho	001D6221	001D0002	MX2D	I, II	I, II
Sagem Morpho	Sagem Morpho	001D6221	001D0003	MX2E	I, II	I, II
Oberthur	ID 3	0415010B	003F0301	MX2F		I, II
Oberthur	ID 3	0415010C	003F0108	MX2G		I, II
Oberthur	ID 3	0415010C	003F0109	MX2H		I, II
Oberthur	ID 3	0415010C	003F0216	MX2I		I, II
Oberthur	ID 3	0415010C	003F0222	MX2J		I, II
Oberthur	ID 3	0415010C	003F0228	MX2K		I, II
Giesecke & Devrient	Giesecke & Devrient	41570001	41570010	MX2M		II
Gemalto	Innovatrics	41580002	00350095	MX2N	III	III
Gemalto	Innovatrics	41580002	00350096	MX2O	III	III
Oberthur	ID 3	1433C6FC10010D	003F0310	MX2P		III
Oberthur	ID 3	1433C6FC10010D	003F0320	MX2Q		III
Gemalto	Micro-PackS	41580001	41610010	MX2R		III
Gemalto	Micro-PackS	41580001	41610011	MX2S		III
Gemalto	Cogent	41580001	00173143	MX2T	III	III
Athena	Neurotechnology	0031FF01	00312002	MX2-IV-A	IV	IV
Athena	Neurotechnology	0031FF01	00312003	MX2-IV-B	IV	IV
Morpho	Morpho	001D9069	001D0004	MX2-IV-C	IV	IV
Morpho	Morpho	001D9232	001D0105	MX2-IV-D	IV	IV
Oberthur	ID3	1433CF0801010E	003F0311	MX2-IV-E	IV	IV
Oberthur	ID3	1433BF0801010E	003F0321	MX2-IV-F	IV	IV
Spyrus	Precise Biometrics	41710300	000B0215	MX2-IV-G	IV	IV
Giesecke & Devrient	Precise Biometrics	41570002	000B0212	MX2-IV-H	IV	IV
Gemalto	Precise Biometrics	41580001	000B0210	MX2-IV-I	IV	IV
Gemalto	Precise Biometrics	41580001	000B0211	MX2-IV-J	IV	IV
Gemalto	Innovatrics	41580001	00350002	MX2-IV-K	IV	IV
Gemalto	Innovatrics	41580002	00350003	MX2-IV-L	IV	IV
Gemalto	Micro-PackS	41580001	41610012	MX2-IV-M		IV
Gemalto	Dermalog	41580001	000D0107	MX2-IV-N		IV
PAV Card	Dermalog	41654165	000D0106	MX2-IV-O		IV
MaskTech	Dermalog	41690001	000D0107	MX2-IV-P		IV
DART	Institute for Infocomm Research	416A0001	416B0001	MX2-IV-Q		IV

Table 1: Teams participating in the four MINEX II phases. Phase III is in blue. The latest Phase IV is in red. This document only publishes results for Phase IV. The last two columns indicate the components the teams elected to submit - the template generator was optional, the matcher was mandatory. Empty cells indicate the provider elected not to participate, or failed to submit according to the deadline. Participation in Phase I or II (2007-2008) was not a pre-requiste of Phase III (2008-2009) which in turn was not required for Phase IV (2010).

Terms and Definitions

Table 2 gives MINEX-specific definitions to various words and acronyms found in this report.

No.	Term	Definition
1	MOC	Match-on-Card
2	SMOC	Secure Match-on-Card
3	ANSI	American National Standards Institute
4	ISO	International Organization for Standardization
5	IEC	International Electrotechnical Commission
6	SC 17	Subcommittee responsible for development of indentfication card standards
7	SC 37	Subcommittee responsible for development of biometrics standards
8	M1	The standards body that formulates comments toward SC 37 biometrics standards
9	INCITS	International Committee for Information Technology Standards
10	INCITS 378:2004	U.S. standard governing the templates
11	ISO/IEC 19795-2:2005	International variant of the INCITS 378 format
12	Compact card	Three-bytes per minutia format defined in ISO/IEC 19794-2:2005
13	Standard template	Record containing standard $(x, y, \theta, type, quality)$ minutiae
14	Proprietary template	Template comparable only with a template from the same vendor
15	Enrollment template	Synonym for reference template
16	Reference template	Template from the first sample of a subject, stored on card
17	Authentication template	Template generated from a second sample of a subject, or from an impostor's sample
18	Matcher	Software function that compares two templates to produce a similarity score
19	Generator	Software function that accepts an image and produces a template
20	Native matching	Comparison by matcher from vendor X of two templates from vendor X's generator
21	BIT	Biometric Information Template (See ISO/IEC 7816)
22	BDB	Biometric Data Block (See SC37's *Harmonized Vocabulary*[1])
23	Genuine	Comparison of templates from the same person
24	Impostor	Comparison of templates from different individuals
25	Verification	One-to-one comparison
26	Authentication	Synonym for verification
27	FAR	False accept rate (i.e. transactional outcome)
28	FRR	False reject rate (i.e. transactional outcome)
29	FMR	False match rate (i.e. 1:1 single sample comparison outcome)
30	FNMR	False non-match rate (i.e. 1:1 single sample comparison outcome)
31	DET	Detection Error Tradeoff characteristic
32	SDK	Software Development Kit
33	APDU	Application Protocol Data Unit
34	API	Application Programming Interface
35	DHS	U. S. Department of Homeland Security
36	NIST	National Institute of Standards and Technology
37	POE	Referring to samples collected in a port of entry
38	BVA	Referring to samples collected as part of a biometric visa application
39	MINEX	The Minutiae Interoperability Exchange program

Table 2: Glossary of MINEX II related terms

1 INTRODUCTION

The approval of the U.S. and international fingerprint minutia template standards, specifically INCITS 378 and ISO/IEC 19794-2:2005 , have created the possibility to establish an interoperable multivendor marketplace for applications involving fast, economic, and accurate interchange and matching of compact biometric templates.

The standards are not application specific. They define formats which can be used for both MATCH-OFF-CARD and MATCH-ON-CARD . While the viability of the templates for MATCH-OFF-CARD has been assessed previously [8, 7, 6], the MATCH-ON-CARD application, which is almost always conceived of as occuring on conformant ISO/IEC 7816 smart cards, has not been independently and publicly tested.

Thus, the MINEX II trial was designed to answer three important and outstanding questions surrounding MATCH-ON-CARD , namely:

- ▷ What is the accuracy loss incurred using the three bytes per minutia ISO/IEC 19794-2 COMPACT CARD format favored for MATCH-ON-CARD , vs. the six bytes per minutia INCITS 378 format?
- ▷ What loss in accuracy is incurred when compact fingerprint minutia templates are matched on ISO/IEC 7816 cards vs. on a resource-rich processor?
- ▷ What is the time needed to execute the algorithmic matching operation?

The first question was addressed in the MINEX II Evaluation Plan [9]. While the last question can be estimated by ad hoc usage, it is the near-term imperative to answer the second question that served as the primary motivator for the MINEX II study.

The results of MINEX II may have implications for projects such as the US Government's Personal Identity Verification (PIV) program[3] and the U.S. Department of Homeland Security's Transportation Worker Identification Credential (TWIC). PIV was initiated by Homeland Security Presidential Directive 12[4]. This mandated the establishment of a common identification standard for federal employees and contractors. It required interoperable identity credentials for physical and logical access to federal government facilities and systems. In response, NIST released FIPS 201[5] in February 2005, which includes the definition of an identity credential. It specified the inclusion of data from two fingerprints as a third authentication factor. The format for this information was finalized in February 2006, when NIST *Special Publication 800-76* specified the MINEX II profile of the INCITS 2004 minutia standard. A broad timeline is given in Table 3.

1.1 Objectives

The MINEX 04 evaluation was intended to assess the viability of the INCITS 378 templates as the interchange medium for fingerprint data. The main objective was to determine whether standardized minutia reference templates can be subsequently matched against an authentication template from another vendor. MINEX II retains this objective but focuses the activity to matchers using ISO/IEC 19794-2 COMPACT CARD templates on ISO/IEC 7816 cards.

MINEX II is intended to measure the core algorithmic capabilities of fingerprint matching algorithms running on standardized ISO/IEC 7816 smart cards. Specifically the MINEX II program has

- ▷ instantiated a mechanism for MATCH-ON-CARD testing,
- ▷ reported accuracy of MATCH-ON-CARD of ISO/IEC 19794-2:2005 compact card minutia templates,
- ▷ timed the various operations, and
- ▷ demonstrated the viability of INCITS 378:2004 as a parent to the ISO/IEC 19794-2 compact card. This leveraged transcoding software available in NIST's open-source BIOMDI (Biometric Data Interchange) repository[6].

[3] See http://csrc.nist.gov/piv-program/

[4] The text of HSPD 12 is here: http://www.whitehouse.gov/news/releases/2004/08/20040827-8.html

[5] See Federal Information Processing Standards Publication 201, *Personal Identity Verification for Federal Employees and Contractors* and related documents here: http://csrc.nist.gov/piv-program

[6] See http://biometrics.nist.gov/nigos

The following are specifically not within the current scope of this evaluation.

- ▷ The ISO/IEC 19794-2 ”record” and ”card normal” templates.
- ▷ Ridge count, core and delta, and zonal quality extensions.
- ▷ Proprietary templates, and non-standard extensions to any standardized minutia format.
- ▷ Evaluation of readers, including performance, conformance and interoperability.
- ▷ Evaluation of ruggedness or durability of the card.
- ▷ On-card template generation (i.e. extraction of minutiae from images).
- ▷ Template update or adaptation.
- ▷ A formal test of conformance to parts of ISO/IEC 7816. However, the test uses ISO/IEC 7816 parts 4 and 11, and conformance to the relevant clauses thereof was required.
- ▷ Devices not conforming to ISO/IEC 7816, including all system-on-card and sense-on-card devices embedding proprietary templates[7].

1.2 Relationship to the MINEX parent program

The wider MINEX program is intended to improve template-based interoperability from the imperfect state reported in MINEX 04 and MTIT[7] toward that achievable with image-based implementations. The approach is to conduct several programs, MINEX II, III, IV etc, each of which will embed development, evaluation, targeted feedback and consultation activities between NIST, industry and other interested parties. Within scope are any issues to do with fingerprint minutiae as an interoperable biometric. Typical outcomes will be measurements of accuracy, processing time, template size, and commentary on the relevant standards, studies of utility of quality measures, calibration information, and new metrics. Two prior tests have been conducted:

- ▷ **MINEX 04** was conducted as an initial comparison of image vs. minutia-based interoperability. It assessed the core algorithmic ability of fingerprint matcher Z to compare minutiae templates from template generators X and Y. It compared the matching accuracy in that case with fully proprietary templates on the same sets of archival images. The test adopted the INCITS 378 template as a base standard. The test is now closed. http://fingeprint.nist.gov/minex04
- ▷ **Ongoing MINEX** is a continuing program of interoperability assessment intended to measure conformance and interoperability of INCITS 378:2004 samples. The test uses one expanded partition of the MINEX 04 data to formulate interoperable groups of matchers and template generators. One client of Ongoing MINEX is the US Government's PIV program which has its own set of criteria against which the interoperable group is formed. The test results are available to other applications or programs which may elect to set their own criteria for interoperable performance. The test remains open[8].

1.3 Relationship to NIST's SBMOC activity

A concurrent and related but procedurally separate activity, SECURE BIOMETRIC MATCH-ON-CARD (SBMOC) FEASIBILITY STUDY was conducted at NIST[9] as a demonstration of MATCH-ON-CARD authentication in which the communications channel was secured, the privacy and integrity of the biometric data was cryptographically protected and the card was authenticated to the reader. This was done using a contactless interface. The operations were timed, with the goal

[7] These devices should only be tested in a live scenario test, with device instrumentation to capture proprietary templates for offline cross-comparison.

[8] For results and participation see http://fingerprint.nist.gov/minex.

[9] MINEX II was run by the Information Access Division. The SBMOC activity was conducted by the Computer Security Division.

No.	Period	Event
1	August 25 1986	Minutiae standardization begins: ANSI/NBS[10]-ICST 1-1986 Data Format for Fingerprint Information Interchange standard.
2	December 12 2003	Initial discussions for MINEX 04 at NIST
3	March 8 2004	INCITS 378 Finalized
4	August 27 2004	Homeland Security Presidential Directive 12 is signed
5	September 21 2004	MINEX 04 is announced publicly
6	February 25 2005	Publication of FEDERAL INFORMATION PROCESSING STANDARD-201
7	September 15 2005	Publication of ISO/IEC 19794-2 Biometric Data Interchange Format - Finger minutiae data
8	December 2005	Amendments to INCITS 378 discussed in Toronto meeting of M1
9	February 1 2006	NIST Special Publication 800-76-1 is released
10	March 6 2006	MINEX 04, NISTIR 7296, is released
11	March 6 2006	ONGOING MINEX is announced
12	March 12 2007	MINEX II Concept document released for comment
13	August 15 2007	MINEX II Test Plan finalized
14	October 14 2007	MINEX II Phase I results returned to suppliers
15	November 15 2007	MINEX II Phase II submission deadline
16	January 16 2008	MINEX II Phase II report is submitted for release
17	June 20 2008	NIST announces the Phase III round of testing
18	March 24 2008	NIST comments toward revision of ISO/IEC 19794-2
19	October 30 2008	MINEX II Phase III submission deadline
20	February 27 2009	Latest CD text of revised ISO/IEC 19794-2
21	March 30 2009	NIST comments toward revision of ISO/IEC 19794-2:2005
22	April 27 2009	MINEX II Phase III report is submitted for release
23	November 23 2009	MINEX II Phase IV is announced
24	March 3 2010	MINEX II Phase IV commences
25	February 18 2011	MINEX II Phase IV report is submitted for release
26	March 8, 2011	Draft of FIPS 201-2 is released for comment
27	April 2011	NIST Special Publication 800-76-2 draft is released for comment
28	April 2011	NIST hosts workshop on FIPS 201 revision

Table 3: MINEX chronology and related events.

of conducting an authentication within 2.5 seconds. The results have been published as NISTIR 7452 *Secure Biometric Match-on-Card Feasibility Report* [5].

Not all participants in the SBMOC entered MINEX II , and vice versa.

2 TEST IMPLEMENTATION

2.1 Concept

The MINEX II evaluation measures MATCH-ON-CARD performance at low false match rates with statistical robustness. This necessitates the execution of very large numbers of genuine and impostor comparisons. These cannot be conducted on physical cards for reasons of total time and card durability. Thus, the fundamental approach to testing is to run a PC-based implementation of the card algorithm, and then to verify that the PC algorithm is the same as that on the card by re-running a subset of the template comparisons on the actual card, and checking that the output similarity scores are identical.

2.2 Procedures

The test was implemented by requiring participants to submit the minutiae matching algorithm as an SDK conforming to the MINEX II API specification and a card supporting the MINEX II APDUs. Both APIs are documented in the accompanying MINEX II Evaluation Plan [9].

Vendor ID	BITs	Min	Max	Sort Order
MX2-IV-A	2	0	68	None Given (0x00)
MX2-IV-B	2	0	68	None Given (0x00)
MX2-IV-C	2	3	128	None Given (0x00)
MX2-IV-D	2	3	128	None Given (0x00)
MX2-IV-E	1	0	60	Y-X Ascending (0x09)
MX2-IV-F	1	0	80	Y-X Ascending (0x09)
MX2-IV-G	2	0	128	None Given (0x00)
MX2-IV-H	2	0	128	None Given (0x00)
MX2-IV-I	2	0	128	None Given (0x00)
MX2-IV-J	2	0	80	None Given (0x00)
MX2-IV-K	2	0	80	Y-X Ascending (0x09)
MX2-IV-L	2	0	80	Y-X Ascending (0x09)
MX2-IV-M	2	0	64	Y-X Ascending (0x09)
MX2-IV-N	2	9	64	Polar Distance Ascending (0x11)
MX2-IV-O	2	9	64	Polar Distance Ascending (0x11)
MX2-IV-P	1	9	64	Polar Distance Ascending (0x11)
MX2-IV-Q	1	10	60	X-Y Ascending (0x05)

Table 4: BIT parameters from the MINEX II cards. In all cases, when a vendor's card had both BITs, they were identical.

NIST authored and released open-source software (see section A.1) for conversion of INCITS 378 to ISO/IEC 19794-2 COMPACT CARD templates. This operation respected the ISO/IEC 7816-11:2004 Biometric Information Template (BIT) parameters for minutia count, and sort order. This process is described in detail in the evaluation plan [9].

Execution of the test can be summarized as a six stage process:

1. Validation of SDK functionality - This procedure has been document previously [8];
2. Validation of MOC functionality - The MATCH-ON-CARD procedure is to execute all necessary APDUs and check for errors.
3. Use of (optional) SDK template generators to produce INCITS 378 templates, and retrieval of baseline ONGOING MINEX templates from archival storage;
4. Reading and storage of ISO/IEC 7816-11:2004 BIT card capability records from the submitted cards. The salient BIT properties are recorded in Table 4;
5. Execution of MATCH-OFF-CARD (i.e. using the SDK). This process embeds on-the-fly conversion of INCITS 378 to ISO/IEC 19794-2 COMPACT CARD templates while respecting the BIT. The number of template comparisons was 2747804 for each matcher tested[11]
6. Repetition of 20000 template comparisons on the card, timing thereof, and crosscheck of matcher scores against the SDK output.
7. None of the comparisons involved impostors presenting left as right, or vice versa.

2.3 Fingerprint datasets

A single corpus of fingerprint images was used for MINEX II testing. This is referred to as the POEBVA data set, and it is identical to that described in the MINEX 04 report [8] except that more samples have been drawn from the same population. The dataset is distinguished from many biometric testing corpora in two valuable ways:

- ▷ First, the enrollment and authentication images are collected at separate locations in different environments with different sensors. The BVA images are collected as part of a non-immigrant visa application process. The POE images are collected later when the subject crosses the U.S. border at a Port of Entry.

[11] This test is repeated for each combination of template generators.

On Card	Off Card
▷ Reference template generator is selected by manufacturer of issuance system, A. Format is ISO/IEC 19794-2. ▷ Matcher is selected by provider of card stock, B. It compares ISO/IEC 19794-2 instances. ▷ Verification generator from reader maufacturer, C. It would extract INCITS 378 data, and convert to ISO/IEC 19794-2. ▷ Often A = B $\neq$ C; rarely A = B = C in which case a fully proprietary template may be considered)	▷ Reference template generator is selected by manufacturer of issuance system, A. Format is INCITS 378 or ISO/IEC 19794-2. ▷ Matcher selected by reader manufacturer, B. It compares either INCITS 378 or ISO/IEC 19794-2 records. ▷ Verification template generator selected by reader manufacturer, C. It prepares a INCITS 378 instance, possibly supplemented with proprietary features. ▷ Often A $\neq$ B, B = C

Table 5: Typical relationships and roles in interoperable applications.

▷ Second, the POE authentication images were collected without human intervention in an autocapture process. This embeds an automated quality-in-the-loop assessment to select the best image, ahead of a timeout. This has the effect of elevating overall quality.

Together these aspects enhance the operational relevance of the MINEX II results.

2.4 Interoperabilty

The MINEX II study addressed the conventional logical or physical access paradigm in which a user's smart card, populated with a reference template provided by vendor A and a matching algorithm from vendor B, is used in an authentication attempt in which a template is generated from an acquired image by the generator from a third vendor, C. This tripartite scenario was examined in MINEX 04 and error rates were generally degraded relative to the case where the verification template generator and matcher were provided by the same supplier, as they may well be in off-card matching. Table 5 summarizes typical bipartite and tripartite relationships in federated interoperable applications.

3 METRICS

3.1 Performance measures

The direct and proper way to quantify accuracy and interoperability is in terms of false non-match and false match error rates, FNMR and FMR. The quantities are computed empirically. If s denotes a matcher comparison score obtained by comparing two samples from the same person, and $M(\tau)$ is the number of such scores below threshold, τ,

$$M(\tau) = \sum_{s \in \mathcal{G}} 1 - H(s - \tau) \tag{1}$$

where $\mathcal{G}$ denotes the set of all genuine comparison scores, and $H(x)$ is the step function defined here as

$$H(x) = \begin{cases} 0 & x < 0 \\ 1 & x \geq 0 \end{cases} \tag{2}$$

The inequality placement ensures that scores equal to the threshold correspond to acceptance. FNMR is then the fraction of genuine comparisons for which the score is below the operating threshold:

$$\text{FNMR}(\tau) = \frac{M(\tau)}{M(\infty)} \tag{3}$$

where $M(\infty)$ is just the number of genuine comparisons considered. Likewise, when s denotes a score obtained by comparing samples from different persons, and $N(\tau)$ is the number of scores at or above threshold, τ,

$$N(\tau) = \sum_{s \in \mathcal{I}} H(s - \tau) \tag{4}$$

where $\mathcal{I}$ denotes the set of all impostor scores. FMR is then the fraction of impostor comparisons resulting in a score less that or equal to the operating threshold:

$$\text{FMR}(\tau) = \frac{N(\tau)}{N(\infty)} \tag{5}$$

FMR is regarded as a measure of security, i.e. the fraction of illegitmate matching attempts that result in success.

These error rates must be understood as being *matching* error rates, not *transactional* rates. The ISO/IEC SC 37 Working Group 5 has established different terms for these rates: FMR and FNMR refer to comparisons of single samples, while FAR and FRR apply to the outcome of a human-system transaction in which a user might, for example, make multiple attempts and multiple finger placements.

3.2 Pooled comparisons

Accuracy depends not only on the MOC algorithm, but also heavily on the template generators used for preparation of the reference and authentication templates. This arises because minutia detection and localization is a non-trivial task for which some algorithms are better than others. It has been demonstrated that matching accuracy often is substantially better if either or both of the templates was produced by the provider of the matching algorithm. While this preference for “home-grown” templates is contrary to the goals of a standard template, it nevertheless remains true because no good, open, standard minutia detection algorithm exists.

Therefore in order to compare matching algorithms, this report (for the first time) uses a template pooling technique for accuracy estimation. This was suggested by a Phase III participant in order to avoid the bias introduced by selecting particular template generators. Pooling is implemented as follows. In Equations 1 and 4 the sets $\mathcal{G}$ and $\mathcal{I}$ are actually the union of comparison scores obtained by comparing templates from $K > 1$ generators applied to the same set of input images. In this case, three pools are used:

- ▷ **Pool 1** corresponds to the templates produced by the $K = 19$ generators listed in Table 6. Most of these suppliers did not take part in the MINEX II evaluation but their templates are archived in support of the ONGOING MINEX program[12].
- ▷ **Pool 2** corresponds to the templates from the $K = 5$ template generators submitted to MINEX II i.e. MX2-IV-{A,C,E,G,K}.
- ▷ **Pool 3** corresponds to the templates from the $K = 24$ template generators present in Pool 1 and 2.

Fingerprint Vendor	NIST ID	IBIA ID
Cogent	A	00170A47
Dermalog	B	000D088E
Bioscrypt	C	00020004
Sagem Morpho	D	001D0100
Neurotechnologija	E	00310100
Innovatrics	F	00350A01
NEC	G	00118201
Cross Match Technologies	N	00180406
L1/Identix	1C	000C0D60
Precise Biometrics	1D	000B0100
XTec	1F	00340035
SecuGen	1G	000A0035
BIO-key International	1J	00300258
Motorola	1L	002E0101
Aware	1M	003B0101
Sonda Technologies	1N	003C0101
Neurotechnologija	1T	00310101
Aware	1Y	003B0102
ImageWare	2A	00430011

Table 6: Suppliers of Ongoing MINEX compliant template generators

Pooling is operationally representative to the extent that verification templates, produced in the field on arbitrary card

[12]See http://fingerprint.nist.gov/minex

readers, come from the minutia detectors in the pool in equal proportions. Practically some products would be more commonly used than others. Operational use cases are shown in Table 5.

3.3 One and two finger matching

This report contains performance estimates for one and two-finger authentication. The single-finger results are obtained by pooling the scores from the left and right index finger comparisons as though they were from different individuals. The performance estimates are therefore representative of single-finger verification applications in which users choose to present either left or right index fingers in equal proportion. This report does not assess the effect of multiple verification attempts because it uses archived datasets with only two impressions per finger. Note, however, that the images were collected using the auto-capture paradigm in which a number of images were collected over an interval of a few seconds, and the best one (according to a commercial quality assessment algorithm) retained.

Two mechanisms were used for combining two-finger matching scores: score-level fusion, and decision-level fusion.

▷ **Score Fusion:** The fused score is simply the sum of the left and right comparison scores:

$$s_{ij} = s_{ij}^{(R)} + s_{ij}^{(L)} \tag{6}$$

where i and j denote the i-th enrolled image and the j-th authentication sample and s is the scalar output of a matcher. This *sum-rule* is a simple yet powerful method for multi-sample fusion, is ubiquitous in the literature [13, 10], and has long had theoretical recommendation [11]. The fused score is compared against a threshold, and error rates are again computed using eqs. 5 and 3.

The use of fusion, however, has significant implications. In sum-rule fusion, FNMR rates drop substantially for a given FMR but there is the attendant requirement to *always* acquire and match samples from both fingers. This will generally double the time, the exception being if two sensors are available and used simultaneously.

▷ **Decision ("OR") Fusion:** The more efficient alternative is to only conditionally acquire and compare the second finger. That is, if recognition of a genuine user or impostor is unsuccessful with the first finger, then the second finger is acquired and matched. This constitutes decision-level "OR" fusion. The idea is that many genuine users will require only a single finger to authenticate while the FMR security objective is met after one or maybe two fingers have been presented.

3.4 Thresholds in the DET computation

As is typical in offline testing [2], this report does not fix an operating threshold but instead uses all the scores from a matcher as thresholds that could be used in actual operation.

This testing practice contrasts with fielded MATCH-ON-CARD applications in which the card is configured with a fixed operating threshold, against which a *decision* is rendered.

For MINEX II we required the SDK and the card to produce integer matcher scores on at most $[0, 65535]$. The advantage over just producing true-false decisions is that it allows a survey over *all* operating points, t, and the production of a DET characteristic. This is a plot of FNMR(t) against FMR(t)[13] and, as the primary output of a biometric performance test, is vital in establishing the tradeoff between the inconvenience associated with incorrect rejection of legitimate users, and the incorrect acceptance of fraudulent users. The production of similarity scores also allows a threshold calibration - i.e. FMR as a function of threshold.

[13] DET characteristics sometimes plot Normal deviates, i.e. a plot in which the FNMR and FMR are (nonlinearly) transformed by the inverse CDF of $N(0, 1)$. This is abandoned here because the score densities are not Normal.

3.5 Thresholds for computation of interoperability matrices

Setting an operational threshold is often a sensitive issue because of implications for security, convenience, throughput, and cost. It is always application specific. Although this report makes no recommendations on threshold setting, it has necessarily adopted "default" performance figures of merit in support of comparison objectives. Unless stated otherwise, the results in this report correspond to the threshold that produces a FMR of 0.01. The figure of merit is the FNMR at that point. The value 0.01 should not be construed as a recommended operating point but as a value at which error rate differences may be readily observed.

The interoperability matrices show FNMR for fixed FMR values, e.g. $f = 0.01$. However, this requires the computation of FNMR(t_0) for $t_0 = \text{FMR}^{-1}(f)$, and while this is trivial for continuous matcher scores it is not so for tied integer scores. The inverse FMR computation is approximate because there is no value for which FMR(t_0) is exactly f. So the threshold actually used, t, is the lowest observed score value for which FMR$(t) \leq f$. In some cases this yields FMR values substantially below the target f. This is a conservative policy decision in the sense that FMR is on the "safe" side of f.

This issue is especially apparent in MATCH-ON-CARD implementations because, as Table 7 shows, some algorithms emit only a limited number of unique scores, perhaps as a result of a need to conserve computational resources. The values are observations over $O(10^7)$ comparisons. In principle, each value can be used as a threshold against which acceptance and rejection decisions are based. The lack of possible impostor values precludes a fine grained setting of security policy. The MINEX 04 matchers exhibited many more unique values. The fused scores used in Table 10 take on more unique values because of the eq.(6) sum.

This issue is not critical for DETs, which plot the error rates at all possible thresholds with straight lines connecting them. Note, that theory indicates [12] that points on the convex hull of the DET curve between two operating thresholds are accessible by randomly using one or the other for each comparison. The operational use of this practice is not known.

	Number of unique score values		
	Genuine	Impostor	All
MX2-IV-A	2706	919	2723
MX2-IV-B	2627	846	2643
MX2-IV-C	19913	8536	20001
MX2-IV-D	19675	8698	19988
MX2-IV-E	31467	4130	31577
MX2-IV-F	31455	4155	31563
MX2-IV-G	8942	586	8942
MX2-IV-H	8920	586	8920
MX2-IV-I	8942	586	8942
MX2-IV-J	8944	587	8944
MX2-IV-K	17289	5405	17766
MX2-IV-L	59758	19693	62139
MX2-IV-M	32749	10284	32752
MX2-IV-N	30238	16567	31829
MX2-IV-O	30238	16567	31829
MX2-IV-P	30238	16567	31829
MX2-IV-Q	1000	533	1001

Table 7: Number of unique similarity scores. The implementations provided in Phases III and IV (from MX2N onwards) produce larger numbers of scores than those prior. Early Oberthur-ID3 algorithms produced fewer than 30 unique impostor scores. The Phase II report concluded that such low numbers inhibit fine-grained threshold setting and FMR.

3.6 Handling failure to enroll

The MINEX test protocols have all required template generators to produce a standard template whatever the input image. Thus if a template generator was presented with an image of such poor quality that it would operationally reject it (i.e. a failure to enroll), the output in MINEX II is nevertheless required to be a template that is a valid input to the matcher. The template is allowed to contain zero minutiae. Such templates are formally conformant to INCITS 378.

When a SDK-based or MOC-based algorithm is presented with a zero minutiae template it will produce a low similarity score (e.g. zero). The effect of this in an impostor comparison is a correct rejection and improved FMR. For a genuine transaction, the result is a false non-match and degraded FNMR .

4 MATCH-ON-CARD ACCURACY

4.1 Uncertainty estimates

This section includes estimates of various false non-match rate (FNMR) and false match rates (FMR). These were estimated over fixed numbers of template comparisons.

- For single finger matching, the number of genuine and impostor comparisons was 247924 and 2499880 respectively corresponding to the use of two impressions of each of the left and right index fingers of 123962 unique subjects. The left index finger from each subject was compared with up to ten other left index fingers. The right index finger was compared with the right index finger of the same individuals. Each finger of each subject was used in only one genuine comparison.
- For two-finger matching, the number of genuine and impostor comparisons was 123962 and 1249940. Again subjects were reused up to ten times.

The error rates follow binomial statistics, such that if experiments of the same size were repeated using samples drawn from the same population then, with 95% coverage, the error rate measurement would fall between $p - u \leq p \leq p + u$ where p is the true error rate,

$$u = \Phi^{-1}_{1-\alpha/2}(p(1-p)/N)^{\frac{1}{2}} \tag{7}$$

Φ^{-1} is the inverse cumulative Normal, and $\alpha = 0.05$. This Normal approximation to the binomial distribution leads to the following estimates of uncertainty.

- for FMR = $p = 0.0001, N = 1249940, u = 0.00002$,
- for FMR = $p = 0.01, N = 1249940, u = 0.0002$, and
- for FNMR = $p = 0.01, N = 123962, u = 0.0006$.
- for FNMR = $p = 0.1, N = 123962, u = 0.0017$.

These estimates apply to the population of fingerprints identified in section 2.3 and do not represent systematic effects associated with the caveats identified on page 3.

4.2 Results

Table 8 is the most important set of results in the report. Each row summarizes MATCH-ON-CARD false non-match rates for one of the algorithms submitted to MINEX II. The left and right sides refers to single-finger and two-finger authentication respectively. For each case, there are four entries corresponding to which minutia detection algorithms were used to prepare the reference and authentication templates. The last of these, referred to as POOL-2 POOL3, represents the case where comparisons of templates from many generators are used in the accuracy calculation. This case is further displayed in the Detection Error Tradeoff (DET) characteristics of Figures 1, 3 and 2. Regarding Table 8 and the DETs, we make the following observations.

- There is a large variation in accuracy between MATCH-ON-CARD matchers. In the operationally relevant range, $0.0001 \leq$ FMR ≤ 0.01, the DETs show that FNMR for the most accurate algorithms is about a factor of three lower than that for the least accurate.
- False non-match rates at FMR $= 0.0001$ are between two and four times worse than those at FMR $= 0.01$.
- The two-finger false non-match rates are an order of magnitude lower than the single-finger rates. This is apparent in the single-finger vs. OR-fused DET plots of Figures 1 and 2, and in the two halves of Table 8.
- The two-finger false non-match rates are often the same for sum-rule and OR-rule fusion. This is apparent in the DET plots of Figures 3 and 2.
- Which templates are used in a comparison also has a large influence on accuracy. For single finger authentication, the use of the MX2-IV-C template generator gives FNMR about two thirds of those achieved using the matcher-provider's native template generator. When two fingers are available, the improvement can exceed a factor of two.

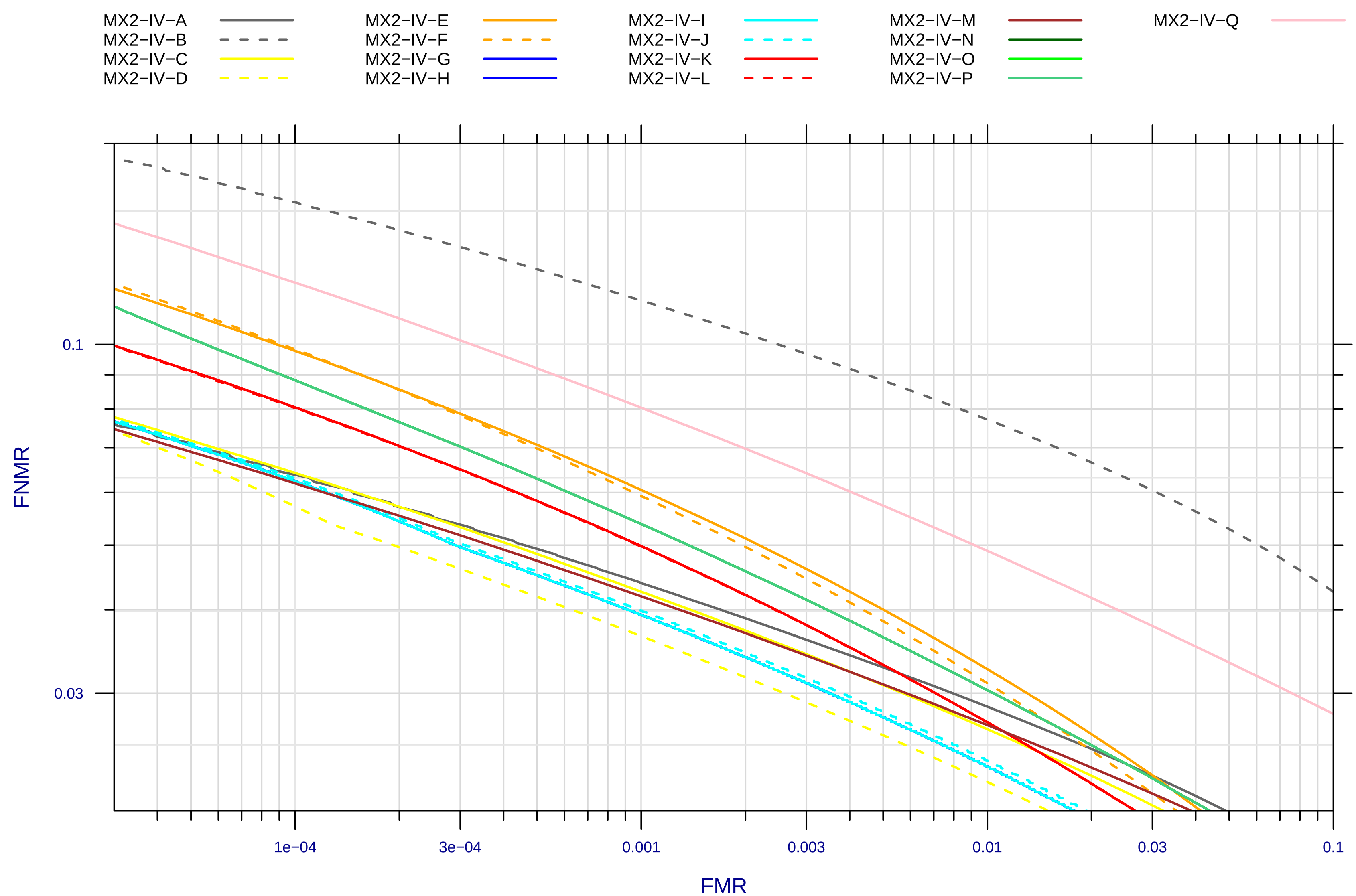


Figure 1: FNMR vs. FMR for all MATCH-ON-CARD algorithms for single finger reference and authentication template comparisons. The reference templates are those of Pool 2. The authentication templates are those of Pool 3 (see section 3.2) such that these DETs are estimated over $5(19+5)N = 120N$ comparisons from each of two fingers, for a total of $240N$. The MX2-IV-{G,H,I} implementations use identical matching algorithms and the plots therefore lie on top of eachother. This holds also for MX2-IV-{N,O,P}.

MX2-IV-A = Neurotechnology-Athena	MX2-IV-B = Neurotechnology-Athena	MX2-IV-C = Morpho-Morpho	MX2-IV-D = Morpho-Morpho
MX2-IV-E = ID3-Oberthur	MX2-IV-F = ID3-Oberthur	MX2-IV-G = Precise Biometrics-Spyrus	MX2-IV-H = Precise Biometrics-G+D
MX2-IV-I = Precise Biometrics-Gemalto	MX2-IV-J = Precise Biometrics-Gemalto	MX2-IV-K = Innovatrics-Gemalto	MX2-IV-L = Innovatrics-Gemalto
MX2-IV-M = Micro-PackS-Gemalto	MX2-IV-N = Dermalog-Gemalto	MX2-IV-O = Dermalog-PAV Card	MX2-IV-P = Dermalog-MaskTech
MX2-IV-Q = Inst Infocomm Rsrch-DART			

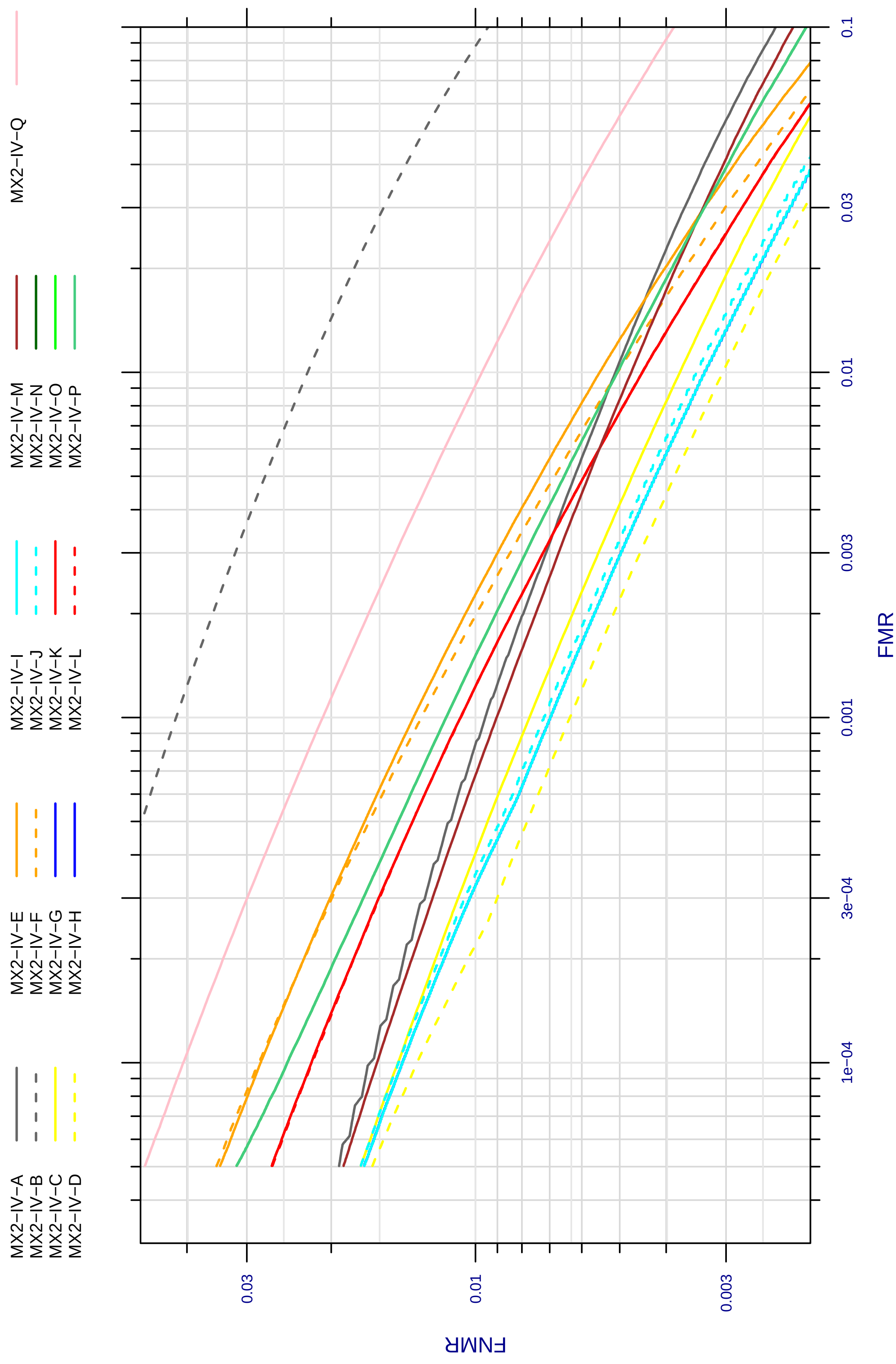


Figure 2: FNMR vs. FMR for all MATCH-ON-CARD algorithms for the left-OR-right finger fusion of reference and authentication template comparisons. The reference templates are those of Pool 2. The authentication templates are those of Pool 3 (see section 3.2) such that these DETs are estimated over $5(19+5)N = 120N$ comparisons. The MX2-IV-{G,H,I} implementations use identical matching algorithms and the plots therefore lie on top of eachother. This holds also for MX2-IV-{N,O,P}.

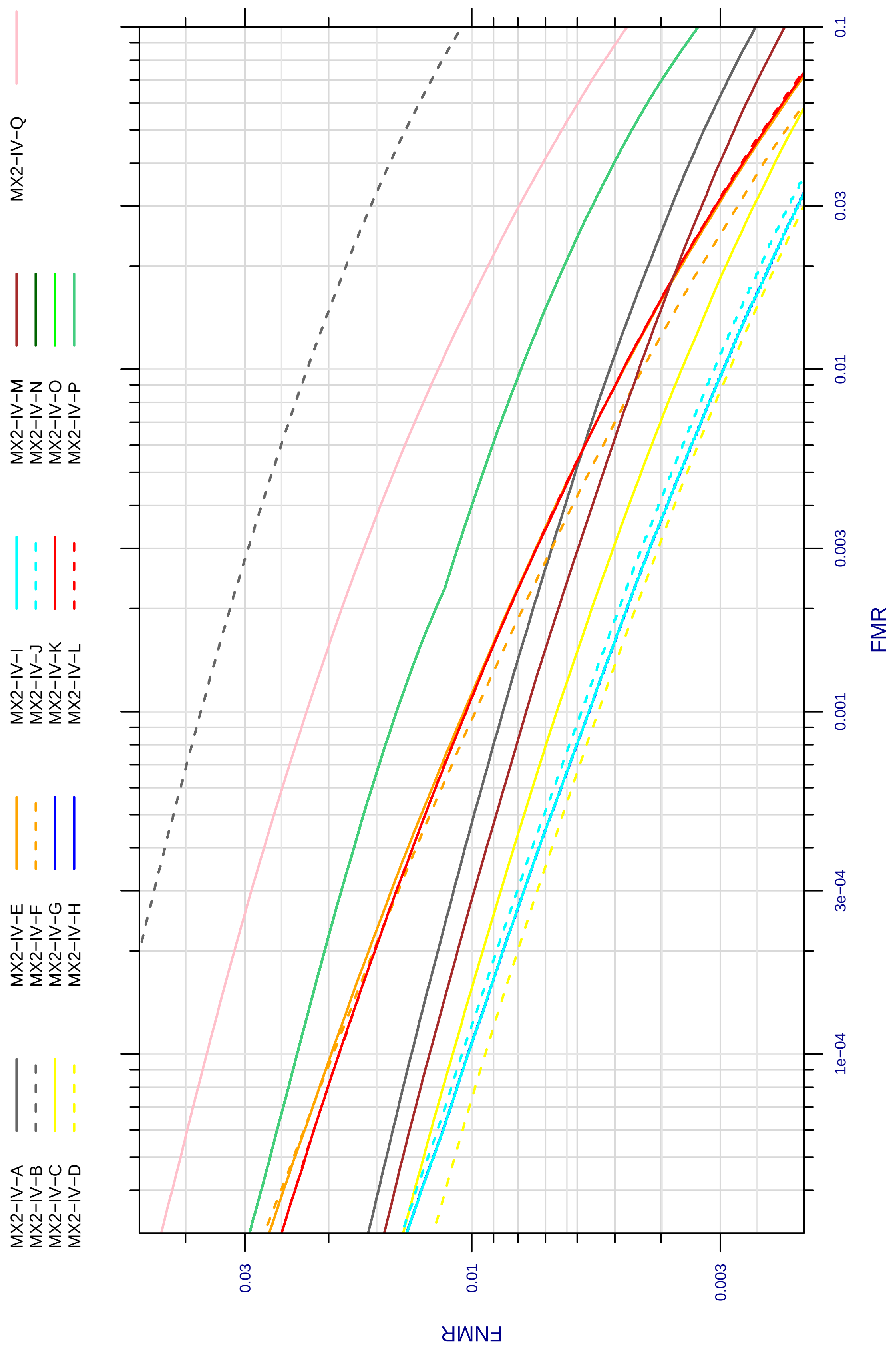


Figure 3: FNMR vs. FMR for all MATCH-ON-CARD algorithms for the sum-rule fusion of scores of left and right finger reference and authentication template comparisons. The reference templates are those of Pool 2. The authentication templates are those of Pool 3 (see section 3.2) such that these DETs are estimated over $5(19+5)N = 120N$ comparisons. The MX2-IV-{G,H,I} implementations use identical matching algorithms and the plots therefore lie on top of eachother. This holds also for MX2-IV-{N,O,P}.

MX2-IV-A = Neurotechnology-Athena	MX2-IV-B = Neurotechnology-Athena	MX2-IV-C = Morpho-Morpho	MX2-IV-D = Morpho-Morpho
MX2-IV-E = ID3-Oberthur	MX2-IV-F = ID3-Oberthur	MX2-IV-G = Precise Biometrics-Spyrus	MX2-IV-H = Precise Biometrics-G+D
MX2-IV-I = Precise Biometrics-Gemalto	MX2-IV-J = Precise Biometrics-Gemalto	MX2-IV-K = Innovatrics-Gemalto	MX2-IV-L = Innovatrics-Gemalto
MX2-IV-M = Micro-PackS-Gemalto	MX2-IV-N = Dermalog-Gemalto	MX2-IV-O = Dermalog-PAV Card	MX2-IV-P = Dermalog-MaskTech
MX2-IV-Q = Inst Infocomm Rsrch-DART			

	SINGLE FINGER				TWO FINGER (OR-FUSED)			
	FMR = 0.0005				FMR = 0.001 (APPROXIMATELY DOUBLE SINGLE-FINGER FMR)			
	BEST-BEST	PREF-PREF	PREF-POOL3	POOL2-POOL3	BEST-BEST	PREF-PREF	PREF-POOL3	POOL2-POOL3
MX2-IV-A	0.0163	0.0372	0.0617	0.0494	0.0015	0.0057	0.0132	0.0095
MX2-IV-B	0.0388	0.0698	0.1537	0.1296	0.0051	0.0148	0.0555	0.0421
MX2-IV-C	0.0179	0.0179	0.0384	0.0485	0.0014	0.0014	0.0051	0.0077
MX2-IV-D	0.0151	0.0151	0.0325	0.0419	0.0012	0.0012	0.0042	0.0064
MX2-IV-E	0.0311	0.0427	0.0707	0.0707	0.0030	0.0053	0.0132	0.0135
MX2-IV-F	0.0314	0.0469	0.0713	0.0698	0.0031	0.0061	0.0132	0.0130
MX2-IV-G	0.0189	0.0327	0.0489	0.0451	0.0017	0.0039	0.0080	0.0070
MX2-IV-H	0.0189	0.0327	0.0489	0.0451	0.0017	0.0040	0.0080	0.0070
MX2-IV-I	0.0189	0.0327	0.0489	0.0451	0.0017	0.0039	0.0080	0.0070
MX2-IV-J	0.0189	0.0327	0.0495	0.0457	0.0017	0.0040	0.0082	0.0072
MX2-IV-K	0.0249	0.0348	0.0535	0.0583	0.0023	0.0044	0.0094	0.0108
MX2-IV-L	0.0247	0.0347	0.0534	0.0582	0.0023	0.0044	0.0094	0.0107
MX2-IV-M	0.0173	0.0240	0.0410	0.0474	0.0017	0.0031	0.0073	0.0090
MX2-IV-N	0.0283	0.0451	0.0629	0.0629	0.0025	0.0060	0.0115	0.0115
MX2-IV-O	0.0283	0.0451	0.0629	0.0629	0.0025	0.0060	0.0115	0.0115
MX2-IV-P	0.0283	0.0451	0.0629	0.0629	0.0025	0.0060	0.0115	0.0115
MX2-IV-Q	0.0441	0.0673	0.0921	0.0921	0.0053	0.0118	0.0208	0.0208

Table 8: FNMR values for single-finger and OR-fused two-finger verification, by MOC algorithm (rows) and template source (columns). The FMR values identified on the second row were selected to be operationally realistic. The two-finger value is twice that of the single finger since MOC implementations using two fingers and a fixed threshold give approximately twice the FMR that would be achieved if only one finger were available (see section 7). For two finger verification, cells are shaded green when FNMR$\leq$ 0.01. For one finger verification, cells are shaded yellow when FNMR$\leq$ 0.025.

The templates come from the four sources indicated in the column headers.

- ▷ BEST-BEST: Both reference and authentication templates are produced by the most interoperable template generator, MX2-IV-C.
- ▷ PREF-PREF: The native case in which the reference and authentication templates come from the matcher's preferred template generator i.e. that supplied with the matcher or the POOL-2 set (see section 3.2) if the provider did not submit a template generator.
- ▷ PREF-POOL3: The authentication templates come from POOL-3, and the reference template comes from the matcher's preferred template generator or from POOL-2 if the provider did not submit a template generator.
- ▷ POOL2-POOL3: The authentication templates come from POOL-3, and the reference templates from POOL-2. The last five rows are identical in the preferred and pooled columns.

The third column is probably the most operationally relevant because MOC algorithms will often reside on cards populated with reference templates generated by the same provider as the matcher. However, the first and fourth columns allow for the purest comparison of just the MOC algorithms because the matchers all compare identical sets of templates.

- ▷ When templates from all sources are used, the FNMR values increase again reflecting the diversity of performance of minutia detectioon algorithms. For single finger authentication, false rejection is approximately 1.5 times to more than 2 times more frequent than if the templates are sourced natively. Specific instances of poor template generation are identified later, in the interoperability matrices of section 6.

- ▷ Pooling represents the use of templates from all generators in equal proportion. This would occur operationally only if system operators ignored performance data in their procurements. The use of pooling here is a form of averaging of results. Thus comparing the third and fourth columns in Table 8, the Neurotechnology and Precise Biometrics algorithms give lower FNMR using Pool 2 templates, because the pool is better overall than their own generator. For Morpho and Innovatrics, Pool 2 gives worse FNMR than the native generators.

- ▷ If decision-level OR-fusion is used by setting a fixed threshold (in the card) and allowing verification with either finger, the FMR values are almost exactly double that of single finger operation. This is detailed later in section 7. Prior versions of this report included an analysis of how often a user would have to present the second finger given some FMR objective.

- ▷ SUM-rule fusion is not shown in Table 8. It is slightly more accurate than decision level left OR right fusion. However, SUM-score fusion is less realistic for MATCH-ON-CARD because the fusion would have to executed on card after presentation of *both* fingers. The OR-fusion is preferable because it is easily implemented on or off the card.

4.3 Can MOC be deployed with one vendor

The attraction of a fully standards-compliant biometrics solution is that credentials issued by one organization can be verified at another organization and there is no requirement that the two organizations buy the same products. The interoperabiliy matrices that appear later in this report indicate that biometric interoperability is not a yes/no variable. Rather, accuracy of a verification application is dependent (as a continuous variable) on which (minutia detection) equipment was originally used to prepare the crediential, and to prepare the authentication template.

If, however, the political and contractual environment was such that MATCH-ON-CARD could be procured from a single vendor then better accuracy can be realized: See the lower error rates in the PREF-PREF columns of Table 8 versus the Pooled columns. In such cases a fully proprietary solution might, in principle, be procured, e.g. by a single corporation seeking to do access control for its employees. However, the buyer is then vulnerable to vendor lock in: Any migration to a new supplier's products necessitates modification or, in the worst case, replacement of all cards and all readers.

A middle ground exists where one supplier's products will be procured, but the solutions will be entirely standards-based. Thus a credential *can* be used with templates from other providers even if it typically is not. Table 8 is intended to show that lower error rates are available **only to the extent** that a single-vendor standards-compliant application is a commercially and politically tenable proposition.

5 MATCH-ON-CARD SPEED

5.1 Measurement method

For each card submitted, NIST measured the duration of all executions of the following actions.

- ▷ Reference template storage operations made using the PUT_DATA APDU,
- ▷ Template comparisons using the VERIFY APDU which includes sending of the verification template to the card, and
- ▷ The similarity score retrieval operations made via the GET_DATA APDU.

The time taken to generate the verification template is not included in the above. For the MX2D generator (of Table 1), the median time to convert an in-memory uncompressed greyscale raster image into an INCITS 378 record was 0.094 seconds for the 368x368 pixel POE verification image and 0.172 seconds for the 500x500 pixel BVA enrolment image. For these two datasets, the 99-th percentile times were, 0.11 and 0.19 seconds respectively. These times apply to Xeon-based PCs.

These times were measured by means of the Linux *gettimeofday()* system call. The NIST card test driver wraps each APDU in two such calls, and the interval is obtained by subtraction. This is shown in the driver source code, which may be downloaded and inspected via the NIST open-source server (see BIOMAPP, section A.2).

While the *gettimeofday()* call offers better than microsecond resolution on the platform we used for testing, the measured durations include more than just the elemental card operations. The overhead includes all the calls to the PC/SC library, communication from the card driver process to the PC/SC smartcard daemon, and USB communication. The effect of these is assumed to be fixed across all MATCH-ON-CARD implementations tested. In particular, the host computer was dedicated to the testing of the cards, with only normal

Team	T PutData	T Verify	T GetData
MX2-IV-A	0.254	0.225	0.033
MX2-IV-B	0.246	0.148	0.033
MX2-IV-C	0.090	0.147	0.021
MX2-IV-D	0.144	0.517	0.026
MX2-IV-E	0.159	0.076	0.017
MX2-IV-F	0.264	0.085	0.017
MX2-IV-G	0.150	0.080	0.018
MX2-IV-H	0.942	1.272	0.029
MX2-IV-I	0.283	0.310	0.020
MX2-IV-J	0.287	0.317	0.020
MX2-IV-K	2.132	1.173	0.028
MX2-IV-L	1.209	1.338	0.120
MX2-IV-M	1.177	0.537	0.024
MX2-IV-N	0.694	0.377	0.023
MX2-IV-O	0.893	0.606	0.021
MX2-IV-P	1.053	0.718	0.035
MX2-IV-Q	0.071	1.007	0.025

Table 9: Three median durations: 1. VERIFY commands for genuine comparisons - more complete information is given in Figure 4. These cells are shaded green and darkgreen for times less than 0.2 and 0.5 seconds respectively. 2. PUTDATA of the reference data. This may be relevant in high volume bulk card preparation processes. 3. GETDATA is fast and only relevant in tests like MINEX II because cards do not return scores operationally.

operating system related and file system processes running. These processes have small system resources overhead.

The hardware listed in Appendix B was disclosed to participants before the test. MINEX II did not test other configurations, and while we understand that faster end-to-end times may be possible using alternative hardware and protocols, the timing method used here is fair and consistent for comparison of implementations.

5.2 Results

Table 9 shows median durations of the ISO/IEC 7816-4 PUTDATA (used for initial installation of the enrollment template), the VERIFY command (for genuine comparisons), and the GETDATA command used to retrieve similarity scores. The speed of the PUTDATA command is operationally irrelevant except perhaps in a bulk card preparation run. The speed of the GETDATA command is fast and only relevant in tests like MINEX II because cards do not return scores operationally.

Figure 4 gives expanded information for the speed of the core MOC command VERIFY. It shows the distributions of the times taken to execute genuine and impostor comparisons. The plots are derived from 1210 genuine and 19424 impostor trials. Note that the card specifications are not known - NIST did not ask for information related to card processor, memory, nor cost. It is likely that suppliers submitted their recent and more capable and expensive cards to the test.

The following observations also summarize the results of Figure 5 which shows the industry-wide tradespace between FNMR and VERIFY time.

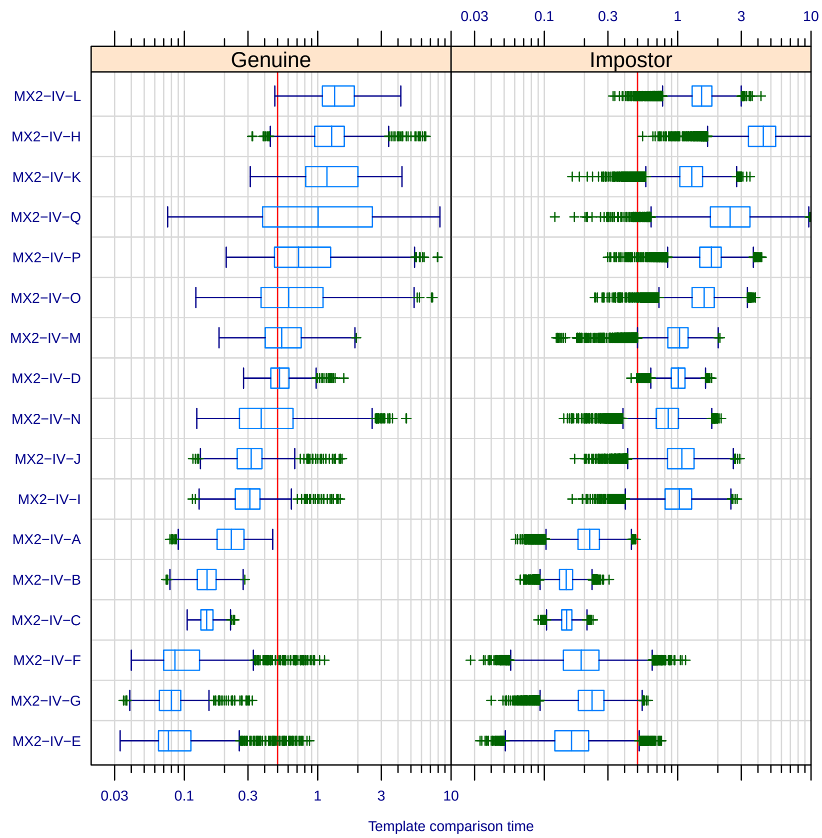


Figure 4: Time for MATCH-ON-CARD verification. The units are seconds. The values are durations of ISO/IEC 7816 VERIFY commands for all MINEX II cards broken out for genuine and impostor comparisons. The duration scale is logarithmic. The vertical red lines are drawn arbitrarily at 0.5 seconds. The boxes indicate the interquartile range. The green crosses indicate outliers beyond those expected in the tails of a Normal distribution.

- ▷ The MX2-IV-E, F and G implementations VERIFY a genuine user in about 0.08 seconds (median). MX2-IV-C completes this in about 0.15 seconds. These were submitted by three different teams (see key at bottom of page). These implementations achieve the PIV interoperability error rate requirements.
- ▷ There are considerable differences in the variances of the times - the MX2-IV-C algorithm compares templates with little variance. The faster algorithms MX2-IV-{E,F,G} all have higher variance and worst-case timings.
- ▷ These times are fast enough that they are becoming a negligible and imperceptible part of the duration of a human authentication attempt.
- ▷ The MX2-IV-F and C implementations run almost four times faster than essentially the same algorithms submitted in Phase III (and listed in Table 1). The MX2-IV-F vs. MX2Q times were 0.085s and 0.294 seconds respectively. The

MX2-IV-C and MX2D times were 0.147 and 0.517 seconds respectively. In addition, the best times are about twice as fast as the fastest implementation tested previously, MX2G, which had a median VERIFY time of 0.16 seconds.

▷ Moreover these speed increases have been obtained with the identical PC/SC hardware and firmware used in prior MINEX II phases. Faster firmware is apparently available from the manufacturer (see Appendix B) although this has not been tested. We maintained the same communications specifications to afford comparability across phases.

▷ The most accurate algorithm, MX2-IV-D from Morpho, takes a median of 0.517 seconds to execute a genuine user's VERIFY APDU.

▷ The four Precise Biometrics implementations submitted on four cards, MX2-IV-G, H, I and J, are equally accurate - they each run almost identical algorithms. The median duration of a MOC comparison is 0.080, 1.272, 0.310 and 0.317 seconds respectively. The order of magnitude variation is related almost entirely to the card in use. This may afford customers a cost-speed tradeoff.

▷ The MX2-IV-K and L meet the PIV interoperability error rate requirements. These card-algorithm pairs have slower median VERIFY durations of 1.173 and 1.338 seconds respectively.

▷ The MX2-IV-M implementation executes in 0.537 seconds. This algorithm, if paired with a suitable template generator, would meet PIV error rate requirements.

6 INTEROPERABILITY

The question of whether a MATCH-ON-CARD matcher would qualify for the U.S. Government's Personal Identity Verification (PIV) program is addressed here by subjecting the MATCH-ON-CARD implementation to the NIST Special Publication 800-76-1 interoperable accuracy specification. This states that a matcher submitted for PIV shall be capable of verifying INCITS 378 templates from all previously qualified template generators. This measurement activity is conducted by NIST under the ONGOING MINEX name. The process requires the supplier of the matcher to also submit a template generator. This requirement derives from the MATCH-OFF-CARD situation in which the reader is equipped with a sensor, template generator and matcher. However, because NIST acceeded to requests from the industry to allow submission of a MATCH-ON-CARD algorithm without an accompanying template generator, we are only able to conduct the following *simulation* of the PIV assessment process.

We use the Table 6 subset of ONGOING MINEX qualified template generators to prepare authentication templates for comparison against others stored on the card. These other templates come from the participant-provided MINEX II submitted generator or the POOL 2 group of generators, or in some cases MX2-IV-C as a capable default. In any case the source of reference templates is show in the column header of the interoperability matrices that follow. This mimics the case in which the issuer of the card were to populate the card with templates from the MOC algorithm owner's generator, from all such suppliers, or by licensing Morpho's new template generator otherwise.

From the interoperability matrices of Tables 10 to 14 we make the observations below. The Tables include, on the third-to-last row (labeled "POOL-1"), the false non-match rates produced when a matcher compares templates from the matcher preferred generator and all templates from all generators listed in Table 6. This represents the operational case of a federated application in which users interact, in equal proporation, with readers equipped with those generators.

▷ From Table 10, the columns shaded entirely green indicate that algorithms MX2-IV-C through MX2-IX-L would attain compliance with the PIV specification[14].

▷ Table 10 shows that the MX2-IX-M implementation meets the PIV interoperability specification. However, it would not do so if coupled with the POOL-2 templates because, when matching authentication templates from Precise

[14]Note that additional template generators have been added to the PIV-compliant list (see http://fingerprint.nist.gov/minex) since this set was initially selected for the MINEX II trials

Nfing 2	Column = MATCH-ON-CARD algorithm MX2-IV-x,										Row = INCITS 378 generator						
Matcher	MX2-IV-A	MX2-IV-B	MX2-IV-C	MX2-IV-D	MX2-IV-E	MX2-IV-F	MX2-IV-G	MX2-IV-H	MX2-IV-I	MX2-IV-J	MX2-IV-K	MX2-IV-L	MX2-IV-M	MX2-IV-N	MX2-IV-O	MX2-IV-P	MX2-IV-Q
Generator	MX2-IV-A	MX2-IV-A	MX2-IV-C	MX2-IV-C	MX2-IV-E	MX2-IV-E	MX2-IV-G	MX2-IV-G	MX2-IV-G	MX2-IV-G	MX2-IV-K	MX2-IV-K	MX2-IV-K	POOL2	POOL2	POOL2	POOL2
A	0.0112	0.0390	0.0027	0.0019	0.0071	0.0072	0.0037	0.0037	0.0037	0.0038	0.0053	0.0053	0.0031	0.0083	0.0083	0.0083	0.0126
B	0.0071	0.0285	0.0020	0.0016	0.0047	0.0042	0.0029	0.0029	0.0029	0.0029	0.0043	0.0044	0.0025	0.0071	0.0071	0.0071	0.0141
C	0.0075	0.0273	0.0027	0.0022	0.0047	0.0038	0.0034	0.0035	0.0034	0.0035	0.0036	0.0036	0.0036	0.0091	0.0091	0.0091	0.0143
D	0.0069	0.0208	0.0016	0.0013	0.0044	0.0043	0.0036	0.0035	0.0035	0.0036	0.0038	0.0037	0.0030	0.0061	0.0061	0.0061	0.0115
E	0.0048	0.0133	0.0032	0.0024	0.0039	0.0039	0.0034	0.0034	0.0034	0.0035	0.0048	0.0049	0.0050	0.0083	0.0083	0.0083	0.0095
F	0.0074	0.0276	0.0027	0.0021	0.0048	0.0038	0.0034	0.0034	0.0034	0.0034	0.0036	0.0036	0.0036	0.0090	0.0090	0.0090	0.0142
G	0.0069	0.0243	0.0021	0.0017	0.0039	0.0033	0.0031	0.0030	0.0031	0.0032	0.0044	0.0044	0.0036	0.0076	0.0076	0.0076	0.0112
N	0.0095	0.0238	0.0043	0.0036	0.0060	0.0061	0.0063	0.0063	0.0063	0.0063	0.0073	0.0072	0.0064	0.0114	0.0114	0.0114	0.0138
1C	0.0032	0.0109	0.0019	0.0013	0.0023	0.0022	0.0021	0.0021	0.0021	0.0021	0.0024	0.0025	0.0024	0.0046	0.0046	0.0046	0.0062
1D	0.0142	0.0362	0.0054	0.0047	0.0075	0.0059	0.0043	0.0043	0.0043	0.0053	0.0077	0.0077	0.0085	0.0166	0.0166	0.0166	0.0201
1F	0.0121	0.0303	0.0042	0.0034	0.0081	0.0071	0.0054	0.0054	0.0054	0.0058	0.0073	0.0074	0.0059	0.0132	0.0132	0.0132	0.0159
1G	0.0121	0.0303	0.0042	0.0034	0.0082	0.0071	0.0054	0.0054	0.0054	0.0058	0.0074	0.0075	0.0060	0.0133	0.0133	0.0133	0.0159
1J	0.0086	0.0235	0.0029	0.0025	0.0070	0.0058	0.0038	0.0038	0.0037	0.0046	0.0038	0.0039	0.0050	0.0123	0.0123	0.0123	0.0174
1L	0.0050	0.0183	0.0020	0.0014	0.0043	0.0042	0.0029	0.0029	0.0029	0.0029	0.0035	0.0034	0.0026	0.0063	0.0063	0.0063	0.0097
1M	0.0072	0.1280	0.0021	0.0017	0.0044	0.0040	0.0036	0.0036	0.0036	0.0036	0.0038	0.0037	0.0028	0.0072	0.0072	0.0072	0.0146
1N	0.0064	0.0198	0.0031	0.0026	0.0044	0.0040	0.0033	0.0034	0.0034	0.0037	0.0036	0.0036	0.0042	0.0086	0.0086	0.0086	0.0110
1T	0.0031	0.0088	0.0019	0.0014	0.0028	0.0027	0.0026	0.0026	0.0026	0.0026	0.0027	0.0026	0.0024	0.0049	0.0049	0.0049	0.0062
1Y	0.0065	0.1329	0.0019	0.0015	0.0040	0.0039	0.0032	0.0032	0.0032	0.0032	0.0035	0.0036	0.0027	0.0067	0.0067	0.0067	0.0130
2A	0.0074	0.0273	0.0027	0.0022	0.0047	0.0038	0.0035	0.0035	0.0034	0.0035	0.0036	0.0036	0.0036	0.0091	0.0091	0.0091	0.0143
MX2D	0.0069	0.0207	0.0016	0.0013	0.0043	0.0043	0.0035	0.0036	0.0036	0.0036	0.0039	0.0037	0.0029	0.0060	0.0060	0.0060	0.0114
MX2-IV-A	0.0030	0.0086	0.0020	0.0013	0.0026	0.0026	0.0025	0.0026	0.0025	0.0025	0.0026	0.0025	0.0024	0.0047	0.0047	0.0047	0.0060
MX2-IV-C	0.0030	0.0111	0.0007	0.0006	0.0023	0.0024	0.0020	0.0019	0.0019	0.0020	0.0022	0.0020	0.0015	0.0033	0.0033	0.0033	0.0060
MX2-IV-E	0.0032	0.0113	0.0015	0.0011	0.0019	0.0020	0.0020	0.0021	0.0020	0.0020	0.0022	0.0022	0.0018	0.0038	0.0038	0.0038	0.0068
MX2-IV-G	0.0033	0.0113	0.0014	0.0011	0.0021	0.0021	0.0018	0.0017	0.0018	0.0018	0.0022	0.0022	0.0016	0.0036	0.0036	0.0036	0.0073
MX2-IV-K	0.0035	0.0137	0.0014	0.0012	0.0023	0.0023	0.0020	0.0021	0.0021	0.0020	0.0020	0.0021	0.0015	0.0040	0.0040	0.0040	0.0085
POOL1	0.0079	0.0349	0.0028	0.0022	0.0052	0.0047	0.0037	0.0037	0.0037	0.0038	0.0046	0.0046	0.0040	0.0088	0.0088	0.0088	0.0130
POOL2	0.0033	0.0114	0.0014	0.0011	0.0023	0.0024	0.0021	0.0021	0.0021	0.0021	0.0022	0.0023	0.0018	0.0039	0.0039	0.0039	0.0070
POOL3	0.0070	0.0303	0.0025	0.0020	0.0046	0.0042	0.0034	0.0034	0.0034	0.0035	0.0042	0.0042	0.0036	0.0079	0.0079	0.0079	0.0118

Table 10: Compliance to the PIV interoperability specification. Sum-fused two-finger FNMR values at FMR = 0.01 for the interoperable case in which the MINEX II matcher identified in the column compares left and right index finger POE authentication templates produced by the generator identified in the row, against corresponding BVA reference templates from the generator supplied with the matching algorithm, or POOL-2 if the supplier did not submit one. Yellow shaded cells indicate *native* combinations - i.e. matcher and template generators from the same provider. Green shaded cells indicate compliance with the PIV error rate specification, FNMR$\leq$ 0.01 at FMR$\leq$ 0.01.

Nfing 2	Column = MATCH-ON-CARD algorithm MX2-IV-x,									Row = INCITS 378 generator							
Matcher	MX2-IV-A	MX2-IV-B	MX2-IV-C	MX2-IV-D	MX2-IV-E	MX2-IV-F	MX2-IV-G	MX2-IV-H	MX2-IV-I	MX2-IV-J	MX2-IV-K	MX2-IV-L	MX2-IV-M	MX2-IV-N	MX2-IV-O	MX2-IV-P	MX2-IV-Q
Generator	POOL 2	POOL 2	POOL 2	POOL 2	POOL 2	POOL 2	POOL 2	POOL 2	POOL 2	POOL 2	POOL 2	POOL 2	POOL 2	POOL 2	POOL 2	POOL 2	POOL 2
A	0.0067	0.0268	0.0065	0.0041	0.0082	0.0082	0.0034	0.0034	0.0034	0.0034	0.0058	0.0059	0.0038	0.0083	0.0083	0.0083	0.0126
B	0.0044	0.0178	0.0033	0.0025	0.0050	0.0045	0.0027	0.0027	0.0027	0.0027	0.0048	0.0048	0.0035	0.0071	0.0071	0.0071	0.0141
C	0.0054	0.0203	0.0033	0.0028	0.0047	0.0038	0.0030	0.0030	0.0030	0.0031	0.0049	0.0049	0.0051	0.0091	0.0091	0.0091	0.0143
D	0.0044	0.0145	0.0030	0.0023	0.0044	0.0043	0.0029	0.0029	0.0029	0.0029	0.0046	0.0045	0.0039	0.0061	0.0061	0.0061	0.0115
E	0.0044	0.0137	0.0042	0.0031	0.0044	0.0044	0.0034	0.0034	0.0033	0.0034	0.0045	0.0046	0.0049	0.0083	0.0083	0.0083	0.0095
F	0.0054	0.0204	0.0033	0.0028	0.0047	0.0038	0.0030	0.0030	0.0030	0.0031	0.0049	0.0049	0.0051	0.0090	0.0090	0.0090	0.0142
G	0.0048	0.0178	0.0032	0.0025	0.0046	0.0039	0.0030	0.0030	0.0030	0.0031	0.0044	0.0044	0.0039	0.0076	0.0076	0.0076	0.0112
N	0.0082	0.0228	0.0061	0.0049	0.0061	0.0062	0.0056	0.0056	0.0056	0.0056	0.0076	0.0075	0.0073	0.0114	0.0114	0.0114	0.0138
1C	0.0024	0.0087	0.0022	0.0017	0.0027	0.0027	0.0021	0.0021	0.0021	0.0021	0.0024	0.0024	0.0024	0.0046	0.0046	0.0046	0.0062
1D	0.0112	0.0287	0.0058	0.0050	0.0079	0.0063	0.0039	0.0039	0.0040	0.0050	0.0091	0.0091	0.0104	0.0166	0.0166	0.0166	0.0201
1F	0.0097	0.0265	0.0065	0.0052	0.0083	0.0072	0.0047	0.0047	0.0047	0.0050	0.0080	0.0080	0.0072	0.0132	0.0132	0.0132	0.0159
1G	0.0097	0.0265	0.0065	0.0052	0.0083	0.0072	0.0047	0.0047	0.0047	0.0050	0.0080	0.0081	0.0072	0.0133	0.0133	0.0133	0.0159
1J	0.0064	0.0186	0.0041	0.0036	0.0068	0.0056	0.0031	0.0031	0.0031	0.0039	0.0051	0.0051	0.0069	0.0123	0.0123	0.0123	0.0174
1L	0.0036	0.0139	0.0033	0.0025	0.0045	0.0042	0.0025	0.0025	0.0025	0.0026	0.0036	0.0037	0.0031	0.0063	0.0063	0.0063	0.0097
1M	0.0048	0.0848	0.0032	0.0025	0.0044	0.0040	0.0029	0.0029	0.0029	0.0029	0.0047	0.0047	0.0040	0.0072	0.0072	0.0072	0.0146
1N	0.0052	0.0166	0.0036	0.0030	0.0047	0.0041	0.0029	0.0029	0.0029	0.0033	0.0043	0.0043	0.0053	0.0086	0.0086	0.0086	0.0110
1T	0.0028	0.0090	0.0022	0.0018	0.0029	0.0028	0.0022	0.0022	0.0022	0.0022	0.0029	0.0029	0.0029	0.0049	0.0049	0.0049	0.0062
1Y	0.0045	0.0886	0.0031	0.0025	0.0040	0.0037	0.0027	0.0027	0.0027	0.0027	0.0043	0.0043	0.0037	0.0067	0.0067	0.0067	0.0130
2A	0.0054	0.0203	0.0033	0.0028	0.0047	0.0038	0.0030	0.0030	0.0030	0.0031	0.0049	0.0049	0.0051	0.0091	0.0091	0.0091	0.0143
MX2D	0.0044	0.0144	0.0030	0.0023	0.0043	0.0043	0.0029	0.0029	0.0029	0.0029	0.0046	0.0045	0.0039	0.0060	0.0060	0.0060	0.0114
MX2-IV-A	0.0027	0.0087	0.0022	0.0018	0.0028	0.0028	0.0022	0.0022	0.0022	0.0022	0.0029	0.0029	0.0028	0.0047	0.0047	0.0047	0.0060
MX2-IV-C	0.0019	0.0074	0.0017	0.0013	0.0026	0.0026	0.0016	0.0016	0.0016	0.0016	0.0022	0.0022	0.0017	0.0033	0.0033	0.0033	0.0060
MX2-IV-E	0.0021	0.0075	0.0020	0.0016	0.0025	0.0025	0.0018	0.0018	0.0018	0.0018	0.0024	0.0024	0.0022	0.0038	0.0038	0.0038	0.0068
MX2-IV-G	0.0023	0.0082	0.0018	0.0014	0.0025	0.0025	0.0017	0.0017	0.0017	0.0017	0.0025	0.0025	0.0021	0.0036	0.0036	0.0036	0.0073
MX2-IV-K	0.0025	0.0094	0.0018	0.0014	0.0025	0.0023	0.0018	0.0018	0.0018	0.0017	0.0027	0.0028	0.0022	0.0040	0.0040	0.0040	0.0085
POOL1	0.0058	0.0256	0.0040	0.0032	0.0054	0.0048	0.0032	0.0032	0.0032	0.0034	0.0053	0.0053	0.0050	0.0088	0.0088	0.0088	0.0130
POOL2	0.0023	0.0083	0.0019	0.0015	0.0026	0.0025	0.0018	0.0018	0.0018	0.0018	0.0026	0.0026	0.0022	0.0039	0.0039	0.0039	0.0070
POOL3	0.0051	0.0222	0.0036	0.0029	0.0048	0.0044	0.0030	0.0030	0.0030	0.0031	0.0048	0.0048	0.0044	0.0079	0.0079	0.0079	0.0118

Table 11: Interoperability matrix showing SUM-fused two-finger FNMR values at FMR = 0.01 for the interoperable case in which the MINEX II matcher identified in the column compares left and right index finger POE authentication templates produced by the generator identified in the row, against corresponding BVA reference templates in POOL-2. This pooling means that in any given row the matching algorithms compare identical sets of templates and this allows comparison of *just* the matching algorithms. This matrix is not the basis of the PIV certification because PIV requires that the matcher identified in the column is accompanied by a template generator. Green shaded cells indicate compliance with the PIV error rate specification, FNMR$\leq$ 0.01 at FMR$\leq$ 0.01.

MX2-IV-A = Neurotechnology-Athena
MX2-IV-B = Neurotechnology-Athena
MX2-IV-C = Morpho-Morpho
MX2-IV-D = Morpho-Morpho
MX2-IV-E = ID3-Oberthur
MX2-IV-F = ID3-Oberthur
MX2-IV-G = Precise Biometrics-Spyrus
MX2-IV-H = Precise Biometrics-G+D
MX2-IV-I = Precise Biometrics-Gemalto
MX2-IV-J = Precise Biometrics-Gemalto
MX2-IV-K = Innovatrics-Gemalto
MX2-IV-L = Innovatrics-Gemalto
MX2-IV-M = Micro-PackS-Gemalto
MX2-IV-N = Dermalog-Gemalto
MX2-IV-O = Dermalog-PAV Card
MX2-IV-P = Dermalog-MaskTech
MX2-IV-Q = Inst Infocomm Rsrch-DART

Nfing 1	Column = MATCH-ON-CARD algorithm MX2-IV-x,										Row = INCITS 378 generator						
Matcher	MX2-IV-A	MX2-IV-B	MX2-IV-C	MX2-IV-D	MX2-IV-E	MX2-IV-F	MX2-IV-G	MX2-IV-H	MX2-IV-I	MX2-IV-J	MX2-IV-K	MX2-IV-L	MX2-IV-M	MX2-IV-N	MX2-IV-O	MX2-IV-P	MX2-IV-Q
Generator	MX2-IV-A	MX2-IV-A	MX2-IV-C	MX2-IV-C	MX2-IV-E	MX2-IV-E	MX2-IV-G	MX2-IV-G	MX2-IV-G	MX2-IV-G	MX2-IV-K	MX2-IV-K	MX2-IV-K	POOL2	POOL2	POOL2	POOL2
A	0.0560	0.1233	0.0260	0.0195	0.0490	0.0490	0.0310	0.0310	0.0310	0.0310	0.0344	0.0341	0.0241	0.0366	0.0366	0.0366	0.0566
B	0.0368	0.0940	0.0193	0.0157	0.0328	0.0309	0.0234	0.0234	0.0234	0.0234	0.0257	0.0260	0.0206	0.0292	0.0292	0.0292	0.0536
C	0.0376	0.0926	0.0231	0.0193	0.0333	0.0298	0.0259	0.0259	0.0259	0.0266	0.0227	0.0226	0.0237	0.0332	0.0332	0.0332	0.0556
D	0.0348	0.0743	0.0157	0.0129	0.0308	0.0304	0.0259	0.0259	0.0259	0.0259	0.0230	0.0231	0.0208	0.0262	0.0261	0.0261	0.0481
E	0.0293	0.0572	0.0234	0.0188	0.0305	0.0305	0.0265	0.0265	0.0264	0.0265	0.0263	0.0263	0.0274	0.0315	0.0315	0.0315	0.0429
F	0.0375	0.0926	0.0229	0.0193	0.0333	0.0299	0.0260	0.0261	0.0260	0.0268	0.0228	0.0226	0.0237	0.0332	0.0332	0.0332	0.0556
G	0.0374	0.0877	0.0215	0.0177	0.0308	0.0291	0.0253	0.0253	0.0253	0.0255	0.0290	0.0288	0.0259	0.0314	0.0314	0.0314	0.0491
N	0.0444	0.0809	0.0288	0.0247	0.0387	0.0391	0.0365	0.0364	0.0365	0.0365	0.0353	0.0351	0.0336	0.0389	0.0389	0.0389	0.0544
1C	0.0229	0.0512	0.0204	0.0155	0.0210	0.0207	0.0190	0.0190	0.0190	0.0190	0.0181	0.0181	0.0174	0.0228	0.0228	0.0228	0.0340
1D	0.0537	0.1012	0.0334	0.0285	0.0411	0.0356	0.0286	0.0287	0.0287	0.0318	0.0354	0.0355	0.0402	0.0454	0.0454	0.0454	0.0674
1F	0.0523	0.0965	0.0289	0.0244	0.0471	0.0442	0.0349	0.0350	0.0350	0.0358	0.0355	0.0358	0.0330	0.0430	0.0430	0.0430	0.0600
1G	0.0525	0.0965	0.0290	0.0245	0.0472	0.0443	0.0350	0.0350	0.0350	0.0358	0.0356	0.0359	0.0331	0.0431	0.0431	0.0431	0.0601
1J	0.0420	0.0820	0.0230	0.0203	0.0435	0.0388	0.0281	0.0280	0.0280	0.0316	0.0255	0.0254	0.0307	0.0393	0.0393	0.0393	0.0652
1L	0.0331	0.0728	0.0192	0.0154	0.0325	0.0317	0.0240	0.0240	0.0240	0.0240	0.0236	0.0235	0.0197	0.0278	0.0278	0.0278	0.0450
1M	0.0379	0.2889	0.0192	0.0157	0.0321	0.0308	0.0271	0.0271	0.0271	0.0271	0.0231	0.0230	0.0212	0.0298	0.0298	0.0298	0.0573
1N	0.0342	0.0707	0.0254	0.0206	0.0307	0.0293	0.0246	0.0246	0.0246	0.0256	0.0225	0.0223	0.0249	0.0301	0.0301	0.0301	0.0475
1T	0.0218	0.0424	0.0180	0.0144	0.0230	0.0226	0.0214	0.0214	0.0214	0.0214	0.0183	0.0184	0.0187	0.0231	0.0232	0.0232	0.0340
1Y	0.0370	0.2943	0.0180	0.0148	0.0305	0.0298	0.0266	0.0267	0.0266	0.0267	0.0225	0.0225	0.0205	0.0290	0.0290	0.0290	0.0543
2A	0.0376	0.0926	0.0231	0.0193	0.0333	0.0299	0.0259	0.0259	0.0260	0.0266	0.0227	0.0226	0.0237	0.0332	0.0332	0.0332	0.0556
MX2D	0.0347	0.0742	0.0157	0.0129	0.0300	0.0304	0.0259	0.0259	0.0260	0.0260	0.0230	0.0230	0.0206	0.0260	0.0260	0.0260	0.0477
MX2-IV-A	0.0217	0.0418	0.0178	0.0143	0.0226	0.0227	0.0214	0.0214	0.0214	0.0213	0.0184	0.0182	0.0183	0.0229	0.0229	0.0229	0.0336
MX2-IV-C	0.0230	0.0524	0.0101	0.0082	0.0225	0.0228	0.0184	0.0184	0.0185	0.0185	0.0163	0.0162	0.0129	0.0193	0.0193	0.0193	0.0334
MX2-IV-E	0.0228	0.0523	0.0156	0.0123	0.0191	0.0196	0.0183	0.0183	0.0184	0.0184	0.0162	0.0162	0.0149	0.0196	0.0196	0.0196	0.0351
MX2-IV-G	0.0236	0.0514	0.0160	0.0127	0.0206	0.0207	0.0168	0.0168	0.0168	0.0168	0.0174	0.0172	0.0146	0.0198	0.0198	0.0198	0.0367
MX2-IV-K	0.0240	0.0588	0.0155	0.0124	0.0218	0.0219	0.0191	0.0191	0.0191	0.0189	0.0157	0.0158	0.0132	0.0205	0.0205	0.0205	0.0399
POOL1	0.0392	0.1037	0.0227	0.0187	0.0348	0.0332	0.0271	0.0271	0.0271	0.0277	0.0266	0.0266	0.0252	0.0327	0.0327	0.0327	0.0524
POOL2	0.0231	0.0519	0.0150	0.0120	0.0215	0.0218	0.0188	0.0189	0.0189	0.0188	0.0169	0.0167	0.0148	0.0204	0.0204	0.0204	0.0358
POOL3	0.0360	0.0935	0.0212	0.0174	0.0321	0.0309	0.0255	0.0255	0.0255	0.0259	0.0247	0.0247	0.0232	0.0303	0.0303	0.0303	0.0490

Table 12: **Single finger** compliance with the PIV interoperability specification. The values are FNMR values at FMR = 0.01 for the interoperable case in which the MINEX II matcher identified in the column compares left and right index finger POE authentication templates produced by the generator identified in the row, against corresponding BVA reference templates from the generator supplied with the matching algorithm or POOL-2 if the supplier did not submit one. Yellow shaded cells indicate *native* combinations - i.e. matcher and template generators from the same provider. Green shaded cells indicate compliance with a *single finger variant* of the PIV error rate specification, FNMR$\leq$ 0.025 at FMR$\leq$ 0.01.

MX2-IV-A = Neurotechnology-Athena
MX2-IV-B = Neurotechnology-Athena
MX2-IV-C = Morpho-Morpho
MX2-IV-D = Morpho-Morpho
MX2-IV-E = ID3-Oberthur
MX2-IV-F = ID3-Oberthur
MX2-IV-G = Precise Biometrics-Spyrus
MX2-IV-H = Precise Biometrics-G+D
MX2-IV-I = Precise Biometrics-Gemalto
MX2-IV-J = Precise Biometrics-Gemalto
MX2-IV-K = Innovatrics-Gemalto
MX2-IV-L = Innovatrics-Gemalto
MX2-IV-M = Micro-PackS-Gemalto
MX2-IV-N = Dermalog-Gemalto
MX2-IV-O = Dermalog-PAV Card
MX2-IV-P = Dermalog-MaskTech
MX2-IV-Q = Inst Infocomm Rsrch-DART

Nfing 2	Column = MATCH-ON-CARD algorithm MX2-IV-x,										Row = INCITS 378 generator						
Matcher	MX2-IV-A	MX2-IV-B	MX2-IV-C	MX2-IV-D	MX2-IV-E	MX2-IV-F	MX2-IV-G	MX2-IV-H	MX2-IV-I	MX2-IV-J	MX2-IV-K	MX2-IV-L	MX2-IV-M	MX2-IV-N	MX2-IV-O	MX2-IV-P	MX2-IV-Q
Generator	MX2-IV-A	MX2-IV-A	MX2-IV-C	MX2-IV-C	MX2-IV-E	MX2-IV-E	MX2-IV-G	MX2-IV-G	MX2-IV-G	MX2-IV-G	MX2-IV-K	MX2-IV-K	MX2-IV-K	POOL2	POOL2	POOL2	POOL2
A	0.0202	0.0643	0.0050	0.0032	0.0168	0.0173	0.0077	0.0077	0.0076	0.0077	0.0124	0.0125	0.0056	0.0164	0.0164	0.0164	0.0249
B	0.0125	0.0458	0.0037	0.0028	0.0105	0.0097	0.0054	0.0054	0.0054	0.0054	0.0092	0.0091	0.0050	0.0133	0.0133	0.0133	0.0259
C	0.0124	0.0442	0.0046	0.0039	0.0106	0.0094	0.0068	0.0068	0.0068	0.0070	0.0077	0.0077	0.0061	0.0164	0.0164	0.0164	0.0266
D	0.0114	0.0331	0.0029	0.0023	0.0089	0.0090	0.0066	0.0066	0.0066	0.0066	0.0080	0.0082	0.0050	0.0112	0.0112	0.0112	0.0211
E	0.0083	0.0221	0.0055	0.0044	0.0082	0.0083	0.0065	0.0065	0.0065	0.0065	0.0103	0.0103	0.0082	0.0152	0.0152	0.0152	0.0179
F	0.0123	0.0441	0.0045	0.0039	0.0106	0.0095	0.0069	0.0069	0.0069	0.0071	0.0077	0.0078	0.0061	0.0164	0.0164	0.0164	0.0266
G	0.0120	0.0400	0.0042	0.0034	0.0091	0.0086	0.0062	0.0062	0.0062	0.0063	0.0107	0.0106	0.0067	0.0144	0.0144	0.0144	0.0219
N	0.0157	0.0374	0.0076	0.0066	0.0136	0.0141	0.0117	0.0116	0.0117	0.0117	0.0150	0.0149	0.0110	0.0207	0.0207	0.0207	0.0259
1C	0.0054	0.0182	0.0037	0.0028	0.0046	0.0045	0.0040	0.0040	0.0040	0.0040	0.0052	0.0053	0.0039	0.0088	0.0088	0.0088	0.0121
1D	0.0225	0.0544	0.0096	0.0083	0.0149	0.0125	0.0081	0.0081	0.0080	0.0096	0.0162	0.0162	0.0142	0.0274	0.0274	0.0274	0.0345
1F	0.0198	0.0480	0.0075	0.0064	0.0186	0.0174	0.0107	0.0107	0.0107	0.0113	0.0154	0.0159	0.0102	0.0233	0.0233	0.0233	0.0298
1G	0.0198	0.0481	0.0075	0.0064	0.0187	0.0175	0.0108	0.0108	0.0107	0.0113	0.0154	0.0159	0.0102	0.0234	0.0234	0.0234	0.0298
1J	0.0137	0.0366	0.0051	0.0045	0.0153	0.0146	0.0071	0.0071	0.0071	0.0088	0.0079	0.0080	0.0084	0.0211	0.0211	0.0211	0.0314
1L	0.0092	0.0313	0.0035	0.0027	0.0104	0.0104	0.0056	0.0056	0.0056	0.0057	0.0078	0.0079	0.0047	0.0121	0.0121	0.0121	0.0193
1M	0.0122	0.2098	0.0038	0.0031	0.0095	0.0090	0.0068	0.0069	0.0068	0.0068	0.0076	0.0075	0.0051	0.0135	0.0135	0.0135	0.0289
1N	0.0106	0.0316	0.0060	0.0045	0.0097	0.0094	0.0060	0.0060	0.0060	0.0064	0.0076	0.0073	0.0071	0.0147	0.0147	0.0148	0.0204
1T	0.0050	0.0140	0.0034	0.0026	0.0054	0.0052	0.0047	0.0047	0.0047	0.0047	0.0055	0.0054	0.0041	0.0092	0.0093	0.0093	0.0120
1Y	0.0111	0.2158	0.0033	0.0027	0.0088	0.0086	0.0065	0.0065	0.0065	0.0066	0.0074	0.0075	0.0048	0.0130	0.0130	0.0130	0.0263
2A	0.0124	0.0442	0.0046	0.0039	0.0106	0.0094	0.0068	0.0069	0.0068	0.0070	0.0077	0.0077	0.0061	0.0164	0.0164	0.0164	0.0266
MX2D	0.0114	0.0329	0.0029	0.0023	0.0086	0.0090	0.0066	0.0066	0.0066	0.0066	0.0080	0.0082	0.0049	0.0110	0.0110	0.0110	0.0209
MX2-IV-A	0.0050	0.0141	0.0034	0.0026	0.0053	0.0054	0.0047	0.0047	0.0047	0.0047	0.0053	0.0053	0.0042	0.0090	0.0090	0.0090	0.0119
MX2-IV-C	0.0054	0.0189	0.0013	0.0011	0.0050	0.0053	0.0039	0.0039	0.0039	0.0039	0.0042	0.0043	0.0025	0.0065	0.0065	0.0065	0.0118
MX2-IV-E	0.0054	0.0190	0.0026	0.0020	0.0041	0.0045	0.0038	0.0038	0.0038	0.0038	0.0044	0.0044	0.0029	0.0074	0.0074	0.0073	0.0130
MX2-IV-G	0.0055	0.0186	0.0026	0.0019	0.0045	0.0047	0.0035	0.0035	0.0036	0.0035	0.0050	0.0049	0.0030	0.0072	0.0072	0.0072	0.0138
MX2-IV-K	0.0061	0.0228	0.0025	0.0019	0.0050	0.0054	0.0038	0.0039	0.0038	0.0038	0.0042	0.0042	0.0026	0.0077	0.0077	0.0077	0.0161
POOL1	0.0134	0.0567	0.0049	0.0041	0.0115	0.0111	0.0071	0.0071	0.0071	0.0074	0.0100	0.0100	0.0069	0.0161	0.0161	0.0161	0.0245
POOL2	0.0055	0.0192	0.0025	0.0019	0.0049	0.0053	0.0040	0.0040	0.0040	0.0040	0.0047	0.0046	0.0030	0.0076	0.0076	0.0076	0.0134
POOL3	0.0119	0.0494	0.0045	0.0036	0.0101	0.0099	0.0065	0.0065	0.0065	0.0067	0.0089	0.0090	0.0061	0.0144	0.0144	0.0144	0.0222

Table 13: Compliance beyond the PIV interoperability specification. Sum-fused two-finger FNMR values at FMR = **0.001** for the interoperable case in which the MINEX II matcher identified in the column compares left and right index finger POE authentication templates produced by the generator identified in the row, against corresponding BVA reference templates from the generator supplied with the matching algorithm or POOL-2 if the supplier did not submit one. Yellow shaded cells indicate *native* combinations - i.e. matcher and template generators from the same provider. Green shaded cells indicate compliance with the PIV false non-match rate specification, FNMR$\leq$ 0.01.

MX2-IV-A = Neurotechnology-Athena
MX2-IV-E = ID3-Oberthur
MX2-IV-I = Precise Biometrics-Gemalto
MX2-IV-M = Micro-PackS-Gemalto
MX2-IV-Q = Inst Infocomm Rsrch-DART

MX2-IV-B = Neurotechnology-Athena
MX2-IV-F = ID3-Oberthur
MX2-IV-J = Precise Biometrics-Gemalto
MX2-IV-N = Dermalog-Gemalto

MX2-IV-C = Morpho-Morpho
MX2-IV-G = Precise Biometrics-Spyrus
MX2-IV-K = Innovatrics-Gemalto
MX2-IV-O = Dermalog-PAV Card

MX2-IV-D = Morpho-Morpho
MX2-IV-H = Precise Biometrics-G+D
MX2-IV-L = Innovatrics-Gemalto
MX2-IV-P = Dermalog-MaskTech

Nfing 2	Column = MATCH-ON-CARD algorithm MX2-IV-x,										Row = INCITS 378 generator						
Matcher	MX2-IV-A	MX2-IV-B	MX2-IV-C	MX2-IV-D	MX2-IV-E	MX2-IV-F	MX2-IV-G	MX2-IV-H	MX2-IV-I	MX2-IV-J	MX2-IV-K	MX2-IV-L	MX2-IV-M	MX2-IV-N	MX2-IV-O	MX2-IV-P	MX2-IV-Q
Generator	MX2-IV-A	MX2-IV-A	MX2-IV-C	MX2-IV-C	MX2-IV-E	MX2-IV-E	MX2-IV-G	MX2-IV-G	MX2-IV-G	MX2-IV-G	MX2-IV-K	MX2-IV-K	MX2-IV-K	POOL2	POOL2	POOL2	POOL2
A	0.0332	0.0974	0.0081	0.0060	0.0323	0.0347	0.0166	0.0166	0.0167	0.0167	0.0240	0.0243	0.0091	0.0315	0.0314	0.0315	0.0417
B	0.0195	0.0664	0.0058	0.0050	0.0193	0.0191	0.0102	0.0103	0.0102	0.0102	0.0182	0.0177	0.0082	0.0214	0.0214	0.0214	0.0410
C	0.0189	0.0647	0.0075	0.0062	0.0200	0.0188	0.0115	0.0115	0.0115	0.0118	0.0144	0.0142	0.0092	0.0259	0.0259	0.0259	0.0422
D	0.0177	0.0478	0.0046	0.0039	0.0174	0.0186	0.0119	0.0118	0.0118	0.0118	0.0154	0.0150	0.0080	0.0184	0.0184	0.0184	0.0340
E	0.0126	0.0335	0.0087	0.0074	0.0163	0.0171	0.0117	0.0117	0.0117	0.0117	0.0181	0.0183	0.0128	0.0253	0.0253	0.0252	0.0294
F	0.0189	0.0651	0.0073	0.0063	0.0200	0.0190	0.0111	0.0112	0.0111	0.0115	0.0143	0.0141	0.0093	0.0260	0.0260	0.0260	0.0422
G	0.0194	0.0604	0.0073	0.0062	0.0177	0.0179	0.0110	0.0110	0.0111	0.0112	0.0207	0.0208	0.0117	0.0238	0.0238	0.0238	0.0365
N	0.0241	0.0526	0.0120	0.0106	0.0267	0.0280	0.0196	0.0197	0.0197	0.0196	0.0267	0.0267	0.0174	0.0320	0.0320	0.0320	0.0415
1C	0.0084	0.0289	0.0062	0.0047	0.0093	0.0098	0.0068	0.0068	0.0068	0.0068	0.0095	0.0093	0.0064	0.0147	0.0147	0.0147	0.0208
1D	0.0327	0.0757	0.0144	0.0128	0.0265	0.0245	0.0138	0.0137	0.0138	0.0157	0.0278	0.0281	0.0217	0.0404	0.0404	0.0404	0.0524
1F	0.0308	0.0696	0.0121	0.0106	0.0369	0.0362	0.0196	0.0195	0.0196	0.0203	0.0285	0.0291	0.0167	0.0361	0.0361	0.0361	0.0468
1G	0.0309	0.0697	0.0121	0.0106	0.0369	0.0363	0.0196	0.0196	0.0196	0.0203	0.0286	0.0292	0.0167	0.0363	0.0363	0.0363	0.0468
1J	0.0203	0.0514	0.0076	0.0068	0.0296	0.0315	0.0124	0.0126	0.0124	0.0148	0.0147	0.0149	0.0124	0.0333	0.0333	0.0333	0.0487
1L	0.0156	0.0473	0.0058	0.0049	0.0207	0.0228	0.0104	0.0104	0.0104	0.0103	0.0156	0.0154	0.0084	0.0200	0.0200	0.0199	0.0323
1M	0.0197	0.3079	0.0062	0.0049	0.0179	0.0178	0.0126	0.0126	0.0126	0.0126	0.0144	0.0143	0.0090	0.0236	0.0236	0.0236	0.0478
1N	0.0163	0.0462	0.0095	0.0077	0.0178	0.0197	0.0100	0.0100	0.0100	0.0107	0.0135	0.0136	0.0108	0.0233	0.0233	0.0233	0.0324
1T	0.0077	0.0209	0.0054	0.0043	0.0100	0.0099	0.0078	0.0078	0.0079	0.0078	0.0101	0.0101	0.0070	0.0156	0.0156	0.0156	0.0203
1Y	0.0181	0.3136	0.0054	0.0046	0.0177	0.0174	0.0119	0.0119	0.0119	0.0119	0.0130	0.0131	0.0079	0.0223	0.0223	0.0223	0.0454
2A	0.0189	0.0647	0.0075	0.0062	0.0200	0.0187	0.0115	0.0116	0.0115	0.0118	0.0145	0.0142	0.0092	0.0259	0.0259	0.0259	0.0422
MX2D	0.0177	0.0477	0.0046	0.0039	0.0170	0.0185	0.0119	0.0119	0.0119	0.0119	0.0154	0.0151	0.0080	0.0181	0.0181	0.0181	0.0337
MX2-IV-A	0.0076	0.0208	0.0052	0.0041	0.0095	0.0099	0.0077	0.0077	0.0077	0.0078	0.0100	0.0101	0.0069	0.0150	0.0150	0.0150	0.0198
MX2-IV-C	0.0086	0.0286	0.0021	0.0018	0.0101	0.0116	0.0068	0.0069	0.0068	0.0068	0.0084	0.0082	0.0039	0.0115	0.0114	0.0115	0.0197
MX2-IV-E	0.0088	0.0292	0.0041	0.0034	0.0083	0.0108	0.0062	0.0062	0.0062	0.0061	0.0085	0.0080	0.0048	0.0124	0.0124	0.0124	0.0216
MX2-IV-G	0.0091	0.0284	0.0040	0.0034	0.0090	0.0096	0.0056	0.0056	0.0056	0.0056	0.0090	0.0089	0.0048	0.0123	0.0122	0.0122	0.0227
MX2-IV-K	0.0094	0.0338	0.0039	0.0032	0.0104	0.0118	0.0068	0.0067	0.0068	0.0067	0.0081	0.0082	0.0041	0.0132	0.0132	0.0132	0.0265
POOL1	0.0209	0.0832	0.0080	0.0067	0.0220	0.0228	0.0126	0.0127	0.0126	0.0130	0.0186	0.0186	0.0111	0.0258	0.0258	0.0258	0.0396
POOL2	0.0089	0.0294	0.0039	0.0032	0.0098	0.0113	0.0067	0.0066	0.0066	0.0066	0.0088	0.0087	0.0049	0.0129	0.0129	0.0129	0.0222
POOL3	0.0186	0.0728	0.0072	0.0060	0.0195	0.0205	0.0115	0.0115	0.0115	0.0118	0.0167	0.0167	0.0099	0.0233	0.0233	0.0233	0.0361

Table 14: Compliance beyond the PIV interoperability specification. Sum-fused two-finger FNMR values at FMR = **0.0001** for the interoperable case in which the MINEX II matcher identified in the column compares left and right index finger POE authentication templates produced by the generator identified in the row, against corresponding BVA reference templates from the generator supplied with the matching algorithm or POOL-2 if the supplier did not submit one. Yellow shaded cells indicate *native* combinations - i.e. matcher and template generators from the same provider. Green shaded cells indicate compliance with the PIV false non-match rate specification, FNMR$\leq$ 0.01.

MX2-IV-A = Neurotechnology-Athena
MX2-IV-E = ID3-Oberthur
MX2-IV-I = Precise Biometrics-Gemalto
MX2-IV-M = Micro-PackS-Gemalto
MX2-IV-Q = Inst Infocomm Rsrch-DART
MX2-IV-B = Neurotechnology-Athena
MX2-IV-F = ID3-Oberthur
MX2-IV-J = Precise Biometrics-Gemalto
MX2-IV-N = Dermalog-Gemalto
MX2-IV-C = Morpho-Morpho
MX2-IV-G = Precise Biometrics-Spyrus
MX2-IV-K = Innovatrics-Gemalto
MX2-IV-O = Dermalog-PAV Card
MX2-IV-D = Morpho-Morpho
MX2-IV-H = Precise Biometrics-G+D
MX2-IV-L = Innovatrics-Gemalto
MX2-IV-P = Dermalog-MaskTech

Biometrics' 1D minutia detector, the FNMR exceeds 0.01. This minutia detector is a legacy algorithm whose performance is inferior to that of the vendor's more recent implementations. The 1D template generator is unlikely to be used in future operations and should be delisted. The template generator combination {1D,MX2T} prevented the Phase III implementation, MX2T (from Cogent Systems), from meeting PIV. If 1D was delisted from Table 6 MX2T would be the PIV criteria for MATCH-OFF-CARD implementations. Note that dedicated MATCH-ON-CARD specifications are being developed for PIV in the forthcoming NIST Special Publication 800-76-2 (expected mid 2011).

- ▷ Five other implementations, from three teams, come reasonably close to attaining PIV compliance. They are MX2-IV-{A,N,O,P,Q}. The false non-match rates exceed the required 0.01 limit for some "difficult" generators. For example, they all fail with templates from generator, 1D, which produces minutia templates that always yield higher than average error rates here and in the ONGOING MINEX program[15] This less-than-ideal behavior is partly a consequence of differing relative sizes of the templates - some minutia generators are more verbose than others - and this difference is a known cause of interoperability problems [3]. In any case, this specific issue and the variations associated with cross-vendor interoperability are both worthy of further investigation and appropriate standardization efforts.
- ▷ Tables 13 and 14 shows that the MX2-IV-C and D implementations would meet the same PIV FNMR ≤ 0.01 requirement if the FMR criterion was a factor of ten lower, i.e. FMR ≤ 0.001. This does not extend to FMR $= 0.0001$, however. This repeats the Phase III result for MX2D which appears to be the same Morpho algorithm as MX2-IV-C.
- ▷ In Phase III, the MX2D algorithm produced an order of magnitude fewer false matches than any other algorithm for a given FNMR . That result is no longer true because the algorithms from Precise Biometrics, Micro-PackS, Innovatrics and to a lesser extent ID3 have improved. However, for the improved Morpho algorithm, column MX2-IV-D of Table 14 (FMR$= 10^{-4}$) is close to the Precise Biometrics algorithm, column MX2-IV-G, of Table 13 (FMR$= 10^{-3}$).
- ▷ As documented previously [8, 7, 9] interoperable error rates are higher when three companies are involved (one for the reference template, another for the verification template, and a third for the matcher provider). Cross-supplier error rates are higher than native because of systematic inconsistencies between implementations on which minutiae are true, false, and missed, and on local placement of minutiae.

6.1 The meaning of PIV compliance

For the many reasons noted on page 3, the error rates measured in large scale offline tests using archival data are not specifically representative of any particular application[16].

However single-image matching evaluations, conducted on massive archival data sets, are extremely valuable because tests are fair and repeatble assessments of accuracy and speed. In particular, the offline nature of the ONGOING MINEX and MINEX II tests makes them suitable for assessing and certifying the core accuracy and interoperability of minutia matching algorithms. That is, the tests are suitable for exposing implementations that are improperly implementing the underyling INCITS 378 and ISO/IEC 19794-2 COMPACT CARD minutiae standards. Thus, while the MINEX trials are necessary for qualification of implementations, and they effectively support operations, they are not sufficient for prediction of fielded performance.

7 THRESHOLD CALIBRATION

Some biometric algorithm providers publish threshold values needed to attain specific false match rates in one-to-one verification comparisons.

[15] The full table of error rates is linked from http://fingerprint.nist.gov/minex under "Test Results".
[16] Except possibly the US-VISIT application, because MINEX II used its images.

The following tables show such FMR calibrations for the Phase IV MATCH-ON-CARD algorithms. These calibrations are based on the impostor comparisons between POE and BVA optical live-scan images. The number of image-pair comparisons is 2499880 including equal numbers of left and right fingers. This is the number used for computation of native mode thresholds. For pooled mode operation, the reference templates are from the preferred provider, and the authentication templates are those in Pool 3. The use of a pool repeats comparisons from the same parent images so there is no added statistical significance for the FMR measurement.

Additionally, the results were computed by adding zero-mean uniform random noise ("jitter") to the integer impostor scores to break ties. The width of the uniform noise distribution was ± 0.2. This technique was described in earlier MINEX II reports. The use of noise causes calibrations for identical algorithms to differ slightly, e.g. between MX2-IV-{O,P}.

The tables have the following numbered columns.

1. $\text{FMR}_N(\tau_N)$ The false match measured for native templates at the native theshold. Native templates are those from the provider-preferred template generator. This value is set as the independent variable in the Tables on the assumption that an algorithm developer would set the native threshold τ_N by calibrating it on vendor-proprietary databases.

2. $\text{FMR}_P(\tau_N)$ The false match measured for pooled templates at the native theshold. The comparisons is of provider-preferred reference templates with Pool 3 templates (see section 3.2).

3. τ_N is the native mode threshold that gives column 1 FMR.

4. τ_P is the threshold that gives the FMR of column 1 over all pooled comparisons. This value serves as the default recommendation for MATCH-ON-CARD implementations sold into a federated marketplace where multiple template generators are in use.

5. $\text{FNMR}_N(\tau_N)$ is the FNMR at the native threshold computed over native comparisons.

6. $\text{FNMR}_P(\tau_N)$ is the FNMR at the native threshold computed over pooled comparisons.

7. $\text{FNMR}_P(\tau_P)$ is the FNMR at the pooled threshold computed over pooled comparisons.

8. $\text{FMR}_N(\tau_N)$ is the FMR when the native single-finger threshold is used but either impostor finger can be used. This is computed over native comparisons.

9. $\text{FMR}_P(\tau_N)$ is the FMR when the native single-finger threshold is used but either impostor finger can be used for authentication. This is computed over pooled comparisons.

10. $\text{FNMR}_P(\tau_N)$ is the FNMR when the native single-finger threshold is used but either genuine finger can be used for authentication. This is computed over pooled comparisons.

11. $\text{FNMR}_P(\tau_P)$ is the FNMR when the pooled single-finger threshold is used but either genuine finger can be used for authentication. This is computed over pooled comparisons.

Color coding.

- ▷ The single finger FMR cells are coded to show deviations in FMR from that expected by setting the threshold based on native-only comparisons. Thus, for single fingers, if FMR is reduced by more than 10% it is shaded green. If FMR increases by more than 10%, 20% or 50% the cell is shaded in increasingly deeper red colors.
- ▷ For OR-fused two-finger authentication, FMR cells are shaded green when is less than 1.8 times the single finger target FMR given in column 1.
- ▷ FNMR cells are never shaded.

Matcher MX2-IV-A Neurotechnology										
Single Finger							OR-fused Two Finger			
$FMR_N(\tau_N)$	$FMR_P(\tau_N)$	τ_N	τ_P	$FNMR_N(\tau_N)$	$FNMR_P(\tau_N)$	$FNMR_P(\tau_P)$	$FMR_N(\tau_N)$	$FMR_P(\tau_N)$	$FNMR_P(\tau_N)$	$FNMR_P(\tau_P)$
0.00003	0.00001	804	757	0.055	0.104	0.094	0.00006	0.00003	0.030	0.026
0.00005	0.00002	772	726	0.052	0.097	0.088	0.00010	0.00005	0.027	0.023
0.00010	0.00005	730	684	0.047	0.088	0.079	0.00020	0.00009	0.023	0.019
0.00030	0.00015	660	616	0.040	0.075	0.067	0.00060	0.00030	0.018	0.015
0.00050	0.00024	629	585	0.037	0.069	0.062	0.00100	0.00049	0.016	0.013
0.00100	0.00052	583	544	0.033	0.061	0.055	0.00202	0.00104	0.013	0.011
0.00300	0.00168	513	479	0.027	0.050	0.045	0.00599	0.00335	0.010	0.008
0.00500	0.00293	480	450	0.025	0.045	0.041	0.01005	0.00588	0.008	0.007
0.01000	0.00617	438	410	0.022	0.040	0.036	0.01969	0.01217	0.007	0.006
0.03000	0.02017	371	349	0.017	0.031	0.028	0.05894	0.03983	0.005	0.004

Matcher MX2-IV-B Neurotechnology										
Single Finger							OR-fused Two Finger			
$FMR_N(\tau_N)$	$FMR_P(\tau_N)$	τ_N	τ_P	$FNMR_N(\tau_N)$	$FNMR_P(\tau_N)$	$FNMR_P(\tau_P)$	$FMR_N(\tau_N)$	$FMR_P(\tau_N)$	$FNMR_P(\tau_N)$	$FNMR_P(\tau_P)$
0.00003	0.00001	726	671	0.105	0.247	0.221	0.00006	0.00002	0.118	0.099
0.00005	0.00002	694	642	0.098	0.232	0.209	0.00010	0.00004	0.107	0.091
0.00010	0.00004	650	602	0.089	0.212	0.191	0.00020	0.00009	0.093	0.079
0.00030	0.00014	582	542	0.075	0.182	0.165	0.00060	0.00028	0.073	0.062
0.00050	0.00025	553	515	0.070	0.170	0.154	0.00099	0.00049	0.065	0.056
0.00100	0.00051	514	478	0.063	0.153	0.139	0.00201	0.00102	0.055	0.047
0.00300	0.00165	453	422	0.052	0.128	0.116	0.00593	0.00326	0.041	0.035
0.00500	0.00286	424	396	0.048	0.117	0.106	0.01000	0.00573	0.036	0.030
0.01000	0.00602	387	361	0.042	0.103	0.094	0.01972	0.01190	0.029	0.024
0.03000	0.02000	326	306	0.033	0.081	0.074	0.05914	0.03968	0.019	0.016

Matcher MX2-IV-C Morpho										
Single Finger							OR-fused Two Finger			
$FMR_N(\tau_N)$	$FMR_P(\tau_N)$	τ_N	τ_P	$FNMR_N(\tau_N)$	$FNMR_P(\tau_N)$	$FNMR_P(\tau_P)$	$FMR_N(\tau_N)$	$FMR_P(\tau_N)$	$FNMR_P(\tau_N)$	$FNMR_P(\tau_P)$
0.00003	0.00002	8012	7814	0.029	0.065	0.061	0.00006	0.00004	0.012	0.011
0.00005	0.00004	7709	7530	0.027	0.059	0.056	0.00010	0.00007	0.010	0.009
0.00010	0.00008	7293	7163	0.024	0.052	0.050	0.00020	0.00015	0.008	0.008
0.00030	0.00024	6686	6574	0.020	0.044	0.042	0.00060	0.00049	0.006	0.006
0.00050	0.00042	6386	6296	0.018	0.040	0.038	0.00100	0.00085	0.005	0.005
0.00100	0.00087	5988	5913	0.016	0.035	0.034	0.00200	0.00174	0.004	0.004
0.00300	0.00256	5381	5288	0.013	0.028	0.027	0.00599	0.00510	0.003	0.003
0.00500	0.00436	5073	4992	0.012	0.025	0.025	0.00996	0.00868	0.003	0.003
0.01000	0.00885	4652	4579	0.010	0.022	0.021	0.01988	0.01760	0.002	0.002
0.03000	0.02745	3948	3891	0.008	0.017	0.016	0.05883	0.05393	0.001	0.001

Matcher MX2-IV-D Morpho										
Single Finger							OR-fused Two Finger			
$FMR_N(\tau_N)$	$FMR_P(\tau_N)$	τ_N	τ_P	$FNMR_N(\tau_N)$	$FNMR_P(\tau_N)$	$FNMR_P(\tau_P)$	$FMR_N(\tau_N)$	$FMR_P(\tau_N)$	$FNMR_P(\tau_N)$	$FNMR_P(\tau_P)$
0.00003	0.00002	8116	7989	0.027	0.060	0.057	0.00006	0.00005	0.010	0.010
0.00005	0.00004	7821	7733	0.024	0.053	0.050	0.00010	0.00008	0.009	0.008
0.00010	0.00008	7489	7373	0.020	0.045	0.043	0.00020	0.00016	0.007	0.006
0.00030	0.00024	6910	6798	0.017	0.037	0.036	0.00060	0.00048	0.005	0.005
0.00050	0.00041	6626	6524	0.015	0.034	0.033	0.00100	0.00083	0.004	0.004
0.00100	0.00084	6240	6146	0.013	0.029	0.029	0.00200	0.00168	0.004	0.003
0.00300	0.00254	5623	5530	0.011	0.024	0.023	0.00600	0.00508	0.003	0.002
0.00500	0.00426	5330	5237	0.010	0.021	0.020	0.00996	0.00849	0.002	0.002
0.01000	0.00873	4911	4830	0.008	0.018	0.017	0.01986	0.01734	0.002	0.002
0.03000	0.02708	4221	4156	0.006	0.014	0.013	0.05886	0.05321	0.001	0.001

MX2-IV-A = Neurotechnology-Athena
MX2-IV-E = ID3-Oberthur
MX2-IV-I = Precise Biometrics-Gemalto
MX2-IV-M = Micro-PackS-Gemalto
MX2-IV-Q = Inst Infocomm Rsrch-DART
MX2-IV-B = Neurotechnology-Athena
MX2-IV-F = ID3-Oberthur
MX2-IV-J = Precise Biometrics-Gemalto
MX2-IV-N = Dermalog-Gemalto
MX2-IV-C = Morpho-Morpho
MX2-IV-G = Precise Biometrics-Spyrus
MX2-IV-K = Innovatrics-Gemalto
MX2-IV-O = Dermalog-PAV Card
MX2-IV-D = Morpho-Morpho
MX2-IV-H = Precise Biometrics-G+D
MX2-IV-L = Innovatrics-Gemalto
MX2-IV-P = Dermalog-MaskTech

Matcher MX2-IV-E ID3										
Single Finger							OR-fused Two Finger			
$FMR_N(\tau_N)$	$FMR_P(\tau_N)$	τ_N	τ_P	$FNMR_N(\tau_N)$	$FNMR_P(\tau_N)$	$FNMR_P(\tau_P)$	$FMR_N(\tau_N)$	$FMR_P(\tau_N)$	$FNMR_P(\tau_N)$	$FNMR_P(\tau_P)$
0.00003	0.00003	6499	6441	0.073	0.124	0.122	0.00006	0.00006	0.033	0.032
0.00005	0.00004	6256	6092	0.068	0.116	0.111	0.00010	0.00008	0.030	0.028
0.00010	0.00007	5875	5619	0.061	0.105	0.098	0.00020	0.00014	0.025	0.023
0.00030	0.00022	5110	4913	0.048	0.084	0.079	0.00060	0.00044	0.018	0.016
0.00050	0.00037	4784	4590	0.043	0.076	0.071	0.00099	0.00073	0.015	0.013
0.00100	0.00073	4355	4164	0.036	0.065	0.060	0.00198	0.00145	0.012	0.010
0.00300	0.00226	3679	3511	0.027	0.049	0.046	0.00590	0.00447	0.007	0.007
0.00500	0.00385	3366	3217	0.024	0.043	0.040	0.00990	0.00766	0.006	0.005
0.01000	0.00794	2951	2819	0.019	0.035	0.032	0.01948	0.01553	0.004	0.004
0.03000	0.02443	2313	2198	0.013	0.024	0.022	0.05760	0.04733	0.002	0.002

Matcher MX2-IV-F ID3										
Single Finger							OR-fused Two Finger			
$FMR_N(\tau_N)$	$FMR_P(\tau_N)$	τ_N	τ_P	$FNMR_N(\tau_N)$	$FNMR_P(\tau_N)$	$FNMR_P(\tau_P)$	$FMR_N(\tau_N)$	$FMR_P(\tau_N)$	$FNMR_P(\tau_N)$	$FNMR_P(\tau_P)$
0.00003	0.00001	7436	6838	0.088	0.147	0.128	0.00006	0.00003	0.044	0.035
0.00005	0.00002	7006	6434	0.079	0.134	0.116	0.00010	0.00005	0.037	0.030
0.00010	0.00005	6421	5916	0.068	0.116	0.102	0.00020	0.00010	0.030	0.024
0.00030	0.00016	5589	5134	0.054	0.092	0.080	0.00060	0.00031	0.020	0.016
0.00050	0.00028	5186	4782	0.047	0.082	0.071	0.00100	0.00056	0.016	0.013
0.00100	0.00058	4680	4320	0.039	0.069	0.060	0.00196	0.00114	0.013	0.010
0.00300	0.00189	3913	3625	0.029	0.051	0.045	0.00591	0.00372	0.008	0.006
0.00500	0.00327	3569	3310	0.024	0.044	0.039	0.00984	0.00648	0.006	0.005
0.01000	0.00682	3119	2887	0.020	0.035	0.031	0.01951	0.01351	0.004	0.004
0.03000	0.02222	2417	2243	0.013	0.023	0.021	0.05747	0.04312	0.002	0.002

8 EVOLUTION OF MOC PERFORMANCE

Figure 5 plots a single accuracy estimate against MATCH-ON-CARD VERIFY time for all algorithms submitted to Phases II, III and IV of MINEX II. These are applied to a specific template generator pair (MX2D-B) because these were used in all phases since MINEX II started in 2007. The Figure attributes these performance estimates to the provider of the fingerprint minutia matching algroithm rather than the card provider. Some of the algorithms have been ported to cards from several providers. While it is assumed that the card is not directly influential on core matching accuracy, it is recognized that a fast card can support slow-but-accurate algorithms, and, for example, allow the algorithm to handle a great range of finger rotation angles.

▷ **Morpho:** The algorithm submitted in Phases II and III, denoted MX2D, now runs more quickly than previously. It is denoted as MX2-IV-C in this report. This speed improvement is probably attributable to changes in the card. A new algorithm, MX2-IV-D offers better accuracy but runs only at speeds comparable with the old algorithm on the old cards, about 0.5 seconds per comparison.

▷ **ID3:** The Phase IV algorithms are faster than the Phase III algorithms, but with little improvement in accuracy. These algorithms are substantially more accurate than the five Phase II variants.

▷ **Precise Biometrics:** The Phase IV algorithms demonstrate a large variation in speed with little variation in accuracy. This is attributable to variations in the cards from the three card providers teaming with Precise Biometrics. Accuracy has improved markedly over that measured, but not published, in Phase I.

▷ **Innovatrics:** The Phase III and IV algorithms show little variation in speed and accuracy.

▷ **Neurotechnology:** The Phase IV algorithms show very large variation in accuracy. Accuracy and speed has improved markedly over that measured, but not published, in Phase I.

▷ **Micro-PackS:** The Phase IV algorithms show very large improvement in accuracy compared to Phase III, with little change in speed.

▷ **Dermalog:** The Phase IV algorithms show a small variation in speed and little variation in accuracy.

Matcher MX2-IV-G Precise Biometrics										
Single Finger							OR-fused Two Finger			
$FMR_N(\tau_N)$	$FMR_P(\tau_N)$	τ_N	τ_P	$FNMR_N(\tau_N)$	$FNMR_P(\tau_N)$	$FNMR_P(\tau_P)$	$FMR_N(\tau_N)$	$FMR_P(\tau_N)$	$FNMR_P(\tau_N)$	$FNMR_P(\tau_P)$
0.00003	0.00002	313	300	0.054	0.084	0.081	0.00006	0.00005	0.019	0.018
0.00005	0.00004	284	274	0.050	0.078	0.075	0.00010	0.00008	0.017	0.016
0.00010	0.00008	251	241	0.045	0.070	0.067	0.00020	0.00016	0.014	0.013
0.00030	0.00026	200	194	0.036	0.055	0.054	0.00059	0.00052	0.010	0.009
0.00050	0.00045	178	174	0.033	0.050	0.049	0.00099	0.00090	0.008	0.008
0.00100	0.00092	150	147	0.028	0.043	0.043	0.00201	0.00185	0.007	0.006
0.00300	0.00278	112	109	0.023	0.034	0.034	0.00594	0.00551	0.005	0.005
0.00500	0.00471	95	94	0.020	0.031	0.030	0.01001	0.00946	0.004	0.004
0.01000	0.00964	75	74	0.017	0.026	0.025	0.01956	0.01886	0.003	0.003
0.03000	0.02913	47	47	0.013	0.019	0.019	0.05924	0.05752	0.002	0.002

Matcher MX2-IV-H Precise Biometrics										
Single Finger							OR-fused Two Finger			
$FMR_N(\tau_N)$	$FMR_P(\tau_N)$	τ_N	τ_P	$FNMR_N(\tau_N)$	$FNMR_P(\tau_N)$	$FNMR_P(\tau_P)$	$FMR_N(\tau_N)$	$FMR_P(\tau_N)$	$FNMR_P(\tau_N)$	$FNMR_P(\tau_P)$
0.00003	0.00002	314	300	0.054	0.085	0.081	0.00006	0.00005	0.019	0.018
0.00005	0.00004	284	274	0.050	0.078	0.075	0.00010	0.00008	0.017	0.016
0.00010	0.00008	251	241	0.045	0.070	0.067	0.00020	0.00016	0.014	0.013
0.00030	0.00026	199	194	0.036	0.055	0.054	0.00061	0.00053	0.010	0.009
0.00050	0.00045	178	174	0.033	0.050	0.049	0.00099	0.00090	0.008	0.008
0.00100	0.00092	150	147	0.028	0.043	0.043	0.00201	0.00185	0.007	0.006
0.00300	0.00278	112	109	0.023	0.034	0.034	0.00594	0.00551	0.005	0.005
0.00500	0.00472	95	94	0.020	0.031	0.030	0.00999	0.00946	0.004	0.004
0.01000	0.00963	75	74	0.017	0.026	0.025	0.01957	0.01886	0.003	0.003
0.03000	0.02912	47	47	0.013	0.019	0.019	0.05925	0.05752	0.002	0.002

Matcher MX2-IV-I Precise Biometrics										
Single Finger							OR-fused Two Finger			
$FMR_N(\tau_N)$	$FMR_P(\tau_N)$	τ_N	τ_P	$FNMR_N(\tau_N)$	$FNMR_P(\tau_N)$	$FNMR_P(\tau_P)$	$FMR_N(\tau_N)$	$FMR_P(\tau_N)$	$FNMR_P(\tau_N)$	$FNMR_P(\tau_P)$
0.00003	0.00002	313	300	0.054	0.084	0.081	0.00006	0.00005	0.019	0.018
0.00005	0.00004	284	274	0.050	0.078	0.075	0.00010	0.00008	0.017	0.016
0.00010	0.00008	251	241	0.045	0.070	0.067	0.00020	0.00016	0.014	0.013
0.00030	0.00026	200	194	0.036	0.055	0.054	0.00059	0.00052	0.010	0.009
0.00050	0.00045	178	174	0.033	0.050	0.049	0.00099	0.00090	0.008	0.008
0.00100	0.00092	150	147	0.028	0.043	0.043	0.00201	0.00185	0.007	0.006
0.00300	0.00278	112	109	0.023	0.034	0.034	0.00594	0.00551	0.005	0.005
0.00500	0.00471	95	94	0.020	0.031	0.030	0.01001	0.00946	0.004	0.004
0.01000	0.00963	75	74	0.017	0.026	0.025	0.01956	0.01886	0.003	0.003
0.03000	0.02912	47	47	0.013	0.019	0.019	0.05924	0.05752	0.002	0.002

Matcher MX2-IV-J Precise Biometrics										
Single Finger							OR-fused Two Finger			
$FMR_N(\tau_N)$	$FMR_P(\tau_N)$	τ_N	τ_P	$FNMR_N(\tau_N)$	$FNMR_P(\tau_N)$	$FNMR_P(\tau_P)$	$FMR_N(\tau_N)$	$FMR_P(\tau_N)$	$FNMR_P(\tau_N)$	$FNMR_P(\tau_P)$
0.00003	0.00002	313	300	0.054	0.085	0.082	0.00006	0.00005	0.020	0.019
0.00005	0.00004	284	274	0.050	0.078	0.076	0.00010	0.00008	0.017	0.016
0.00010	0.00008	251	241	0.045	0.070	0.067	0.00020	0.00016	0.014	0.013
0.00030	0.00026	200	194	0.036	0.056	0.054	0.00059	0.00052	0.010	0.009
0.00050	0.00045	178	174	0.033	0.050	0.049	0.00099	0.00089	0.008	0.008
0.00100	0.00092	150	147	0.028	0.044	0.043	0.00201	0.00185	0.007	0.007
0.00300	0.00278	112	109	0.023	0.035	0.034	0.00594	0.00551	0.005	0.005
0.00500	0.00471	95	94	0.020	0.031	0.031	0.01001	0.00946	0.004	0.004
0.01000	0.00964	75	74	0.017	0.026	0.026	0.01956	0.01884	0.003	0.003
0.03000	0.02909	47	47	0.013	0.019	0.019	0.05924	0.05747	0.002	0.002

Matcher MX2-IV-K Innovatrics										
Single Finger							OR-fused Two Finger			
$\mathrm{FMR}_N(\tau_N)$	$\mathrm{FMR}_P(\tau_N)$	τ_N	τ_P	$\mathrm{FNMR}_N(\tau_N)$	$\mathrm{FNMR}_P(\tau_N)$	$\mathrm{FNMR}_P(\tau_P)$	$\mathrm{FMR}_N(\tau_N)$	$\mathrm{FMR}_P(\tau_N)$	$\mathrm{FNMR}_P(\tau_N)$	$\mathrm{FNMR}_P(\tau_P)$
0.00003	0.00003	5293	5304	0.062	0.091	0.092	0.00006	0.00006	0.022	0.022
0.00005	0.00005	5157	5170	0.056	0.083	0.084	0.00010	0.00010	0.019	0.019
0.00010	0.00011	4950	4975	0.048	0.072	0.074	0.00020	0.00022	0.015	0.016
0.00030	0.00031	4666	4677	0.039	0.059	0.060	0.00060	0.00062	0.011	0.011
0.00050	0.00053	4514	4532	0.035	0.053	0.053	0.00100	0.00106	0.009	0.009
0.00100	0.00112	4291	4325	0.029	0.044	0.046	0.00198	0.00222	0.007	0.007
0.00300	0.00328	3954	3983	0.022	0.034	0.035	0.00593	0.00649	0.005	0.005
0.00500	0.00543	3788	3816	0.019	0.029	0.030	0.00985	0.01071	0.004	0.004
0.01000	0.01076	3554	3580	0.016	0.024	0.025	0.01955	0.02101	0.003	0.003
0.03000	0.03187	3155	3178	0.011	0.017	0.017	0.05724	0.06076	0.002	0.002

Matcher MX2-IV-L Innovatrics										
Single Finger							OR-fused Two Finger			
$\mathrm{FMR}_N(\tau_N)$	$\mathrm{FMR}_P(\tau_N)$	τ_N	τ_P	$\mathrm{FNMR}_N(\tau_N)$	$\mathrm{FNMR}_P(\tau_N)$	$\mathrm{FNMR}_P(\tau_P)$	$\mathrm{FMR}_N(\tau_N)$	$\mathrm{FMR}_P(\tau_N)$	$\mathrm{FNMR}_P(\tau_N)$	$\mathrm{FNMR}_P(\tau_P)$
0.00003	0.00003	21121	21209	0.061	0.090	0.092	0.00006	0.00007	0.022	0.022
0.00005	0.00006	20543	20656	0.055	0.082	0.084	0.00010	0.00011	0.019	0.019
0.00010	0.00011	19830	19892	0.049	0.073	0.074	0.00020	0.00021	0.015	0.016
0.00030	0.00032	18611	18689	0.039	0.059	0.059	0.00060	0.00064	0.011	0.011
0.00050	0.00053	18032	18113	0.035	0.053	0.053	0.00100	0.00107	0.009	0.009
0.00100	0.00111	17162	17285	0.029	0.044	0.046	0.00199	0.00220	0.007	0.007
0.00300	0.00328	15800	15913	0.022	0.034	0.035	0.00594	0.00648	0.005	0.005
0.00500	0.00543	15135	15246	0.019	0.029	0.030	0.00984	0.01071	0.004	0.004
0.01000	0.01073	14203	14301	0.016	0.024	0.025	0.01955	0.02097	0.003	0.003
0.03000	0.03190	12600	12695	0.011	0.017	0.017	0.05735	0.06090	0.002	0.002

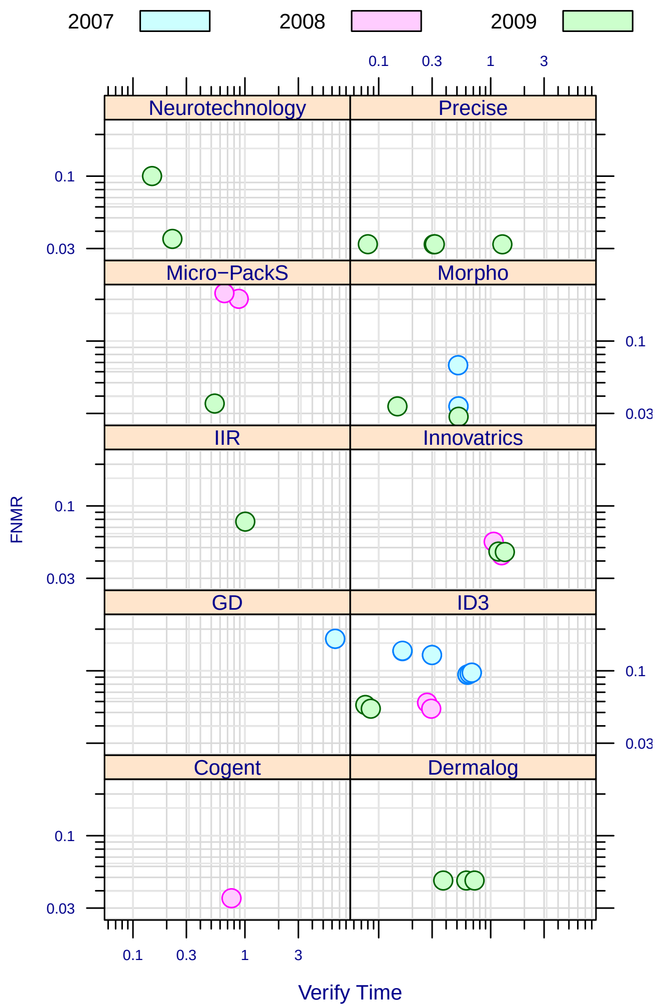
Matcher MX2-IV-M Micro-PackS										
Single Finger							OR-fused Two Finger			
$\mathrm{FMR}_N(\tau_N)$	$\mathrm{FMR}_P(\tau_N)$	τ_N	τ_P	$\mathrm{FNMR}_N(\tau_N)$	$\mathrm{FNMR}_P(\tau_N)$	$\mathrm{FNMR}_P(\tau_P)$	$\mathrm{FMR}_N(\tau_N)$	$\mathrm{FMR}_P(\tau_N)$	$\mathrm{FNMR}_P(\tau_N)$	$\mathrm{FNMR}_P(\tau_P)$
0.00003	0.00002	9973	9716	0.040	0.067	0.065	0.00006	0.00005	0.015	0.015
0.00005	0.00005	9158	9055	0.036	0.061	0.060	0.00010	0.00009	0.013	0.013
0.00010	0.00010	8257	8220	0.032	0.054	0.054	0.00020	0.00019	0.011	0.011
0.00030	0.00030	6945	6937	0.026	0.045	0.045	0.00060	0.00060	0.008	0.008
0.00050	0.00049	6380	6364	0.024	0.041	0.041	0.00100	0.00098	0.007	0.007
0.00100	0.00097	5637	5604	0.021	0.036	0.036	0.00200	0.00194	0.006	0.006
0.00300	0.00288	4490	4449	0.017	0.030	0.029	0.00598	0.00574	0.005	0.004
0.00500	0.00483	3973	3939	0.015	0.027	0.027	0.00994	0.00961	0.004	0.004
0.01000	0.00963	3319	3284	0.013	0.023	0.023	0.01979	0.01906	0.003	0.003
0.03000	0.02871	2396	2363	0.010	0.018	0.018	0.05842	0.05599	0.002	0.002

Matcher MX2-IV-N Dermalog										
Single Finger							OR-fused Two Finger			
$\mathrm{FMR}_N(\tau_N)$	$\mathrm{FMR}_P(\tau_N)$	τ_N	τ_P	$\mathrm{FNMR}_N(\tau_N)$	$\mathrm{FNMR}_P(\tau_N)$	$\mathrm{FNMR}_P(\tau_P)$	$\mathrm{FMR}_N(\tau_N)$	$\mathrm{FMR}_P(\tau_N)$	$\mathrm{FNMR}_P(\tau_N)$	$\mathrm{FNMR}_P(\tau_P)$
0.00003	0.00003	16412	16507	0.053	0.098	0.100	0.00006	0.00007	0.023	0.023
0.00005	0.00005	16013	16002	0.048	0.089	0.089	0.00010	0.00010	0.020	0.020
0.00010	0.00009	15436	15376	0.041	0.078	0.077	0.00020	0.00019	0.016	0.015
0.00030	0.00025	14567	14399	0.032	0.064	0.061	0.00060	0.00050	0.011	0.011
0.00050	0.00041	14135	13949	0.028	0.057	0.054	0.00100	0.00081	0.010	0.009
0.00100	0.00081	13504	13313	0.024	0.049	0.046	0.00200	0.00162	0.008	0.007
0.00300	0.00245	12475	12280	0.018	0.037	0.035	0.00596	0.00489	0.005	0.005
0.00500	0.00415	11957	11768	0.015	0.032	0.031	0.00993	0.00825	0.004	0.004
0.01000	0.00847	11221	11043	0.012	0.027	0.026	0.01970	0.01672	0.003	0.003
0.03000	0.02606	9949	9778	0.009	0.020	0.019	0.05824	0.05075	0.002	0.002

Matcher MX2-IV-O Dermalog										
Single Finger							OR-fused Two Finger			
$FMR_N(\tau_N)$	$FMR_P(\tau_N)$	τ_N	τ_P	$FNMR_N(\tau_N)$	$FNMR_P(\tau_N)$	$FNMR_P(\tau_P)$	$FMR_N(\tau_N)$	$FMR_P(\tau_N)$	$FNMR_P(\tau_N)$	$FNMR_P(\tau_P)$
0.00003	0.00003	32821	33014	0.053	0.098	0.100	0.00006	0.00007	0.023	0.023
0.00005	0.00005	32027	32005	0.048	0.089	0.089	0.00010	0.00010	0.020	0.020
0.00010	0.00009	30875	30751	0.041	0.078	0.077	0.00020	0.00019	0.016	0.015
0.00030	0.00025	29136	28800	0.032	0.064	0.061	0.00060	0.00050	0.011	0.011
0.00050	0.00041	28269	27898	0.028	0.057	0.054	0.00100	0.00081	0.010	0.009
0.00100	0.00081	27007	26626	0.024	0.049	0.046	0.00200	0.00163	0.008	0.007
0.00300	0.00246	24949	24560	0.018	0.037	0.035	0.00597	0.00489	0.005	0.005
0.00500	0.00415	23915	23537	0.015	0.032	0.031	0.00993	0.00825	0.004	0.004
0.01000	0.00847	22441	22086	0.012	0.027	0.026	0.01970	0.01672	0.003	0.003
0.03000	0.02606	19899	19556	0.009	0.020	0.019	0.05824	0.05075	0.002	0.002

Matcher MX2-IV-P Dermalog										
Single Finger							OR-fused Two Finger			
$FMR_N(\tau_N)$	$FMR_P(\tau_N)$	τ_N	τ_P	$FNMR_N(\tau_N)$	$FNMR_P(\tau_N)$	$FNMR_P(\tau_P)$	$FMR_N(\tau_N)$	$FMR_P(\tau_N)$	$FNMR_P(\tau_N)$	$FNMR_P(\tau_P)$
0.00003	0.00003	32822	33012	0.053	0.098	0.100	0.00006	0.00007	0.023	0.023
0.00005	0.00005	32028	32005	0.048	0.089	0.089	0.00010	0.00010	0.020	0.020
0.00010	0.00009	30875	30751	0.041	0.078	0.077	0.00020	0.00019	0.016	0.015
0.00030	0.00025	29136	28800	0.032	0.064	0.061	0.00060	0.00050	0.011	0.011
0.00050	0.00041	28268	27898	0.028	0.057	0.054	0.00100	0.00081	0.010	0.009
0.00100	0.00081	27008	26625	0.024	0.049	0.046	0.00200	0.00162	0.008	0.007
0.00300	0.00246	24949	24561	0.018	0.037	0.035	0.00597	0.00489	0.005	0.005
0.00500	0.00415	23915	23537	0.015	0.032	0.031	0.00993	0.00825	0.004	0.004
0.01000	0.00847	22440	22086	0.012	0.027	0.026	0.01970	0.01672	0.003	0.003
0.03000	0.02606	19899	19556	0.009	0.020	0.019	0.05824	0.05075	0.002	0.002

Matcher MX2-IV-Q Inst Infocomm Rsrch										
Single Finger							OR-fused Two Finger			
$FMR_N(\tau_N)$	$FMR_P(\tau_N)$	τ_N	τ_P	$FNMR_N(\tau_N)$	$FNMR_P(\tau_N)$	$FNMR_P(\tau_P)$	$FMR_N(\tau_N)$	$FMR_P(\tau_N)$	$FNMR_P(\tau_N)$	$FNMR_P(\tau_P)$
0.00003	0.00003	410	408	0.076	0.134	0.133	0.00006	0.00006	0.037	0.037
0.00005	0.00004	396	393	0.070	0.124	0.122	0.00010	0.00009	0.033	0.032
0.00010	0.00009	376	372	0.061	0.110	0.108	0.00020	0.00018	0.027	0.026
0.00030	0.00027	343	340	0.049	0.089	0.088	0.00060	0.00054	0.020	0.019
0.00050	0.00046	327	325	0.044	0.081	0.080	0.00101	0.00093	0.017	0.016
0.00100	0.00093	306	304	0.038	0.070	0.069	0.00201	0.00189	0.013	0.013
0.00300	0.00288	273	271	0.030	0.055	0.055	0.00590	0.00566	0.009	0.009
0.00500	0.00483	256	255	0.026	0.049	0.049	0.01003	0.00968	0.007	0.007
0.01000	0.00971	234	233	0.022	0.042	0.042	0.01949	0.01894	0.006	0.006
0.03000	0.02984	193	193	0.017	0.032	0.032	0.05767	0.05745	0.004	0.004



Matcher	Provider	Year	FNMR	Duration
MX2D	Morpho	2007	0.03	0.52
MX2E	Morpho	2007	0.07	0.51
MX2G	ID3	2007	0.14	0.16
MX2H	ID3	2007	0.13	0.30
MX2I	ID3	2007	0.09	0.62
MX2J	ID3	2007	0.10	0.65
MX2K	ID3	2007	0.10	0.68
MX2M	GD	2007	0.17	6.40
MX2N	Innovatrics	2008	0.06	1.06
MX2O	Innovatrics	2008	0.04	1.25
MX2P	ID3	2008	0.06	0.27
MX2Q	ID3	2008	0.05	0.29
MX2R	Micro-PackS	2008	0.20	0.88
MX2S	Micro-PackS	2008	0.22	0.66
MX2T	Cogent	2008	0.04	0.76
MX2-IV-A	Neurotechnology	2009	0.04	0.22
MX2-IV-B	Neurotechnology	2009	0.10	0.15
MX2-IV-C	Morpho	2009	0.03	0.15
MX2-IV-D	Morpho	2009	0.03	0.52
MX2-IV-E	ID3	2009	0.06	0.08
MX2-IV-F	ID3	2009	0.05	0.08
MX2-IV-G	Precise	2009	0.03	0.08
MX2-IV-H	Precise	2009	0.03	1.27
MX2-IV-I	Precise	2009	0.03	0.31
MX2-IV-J	Precise	2009	0.03	0.32
MX2-IV-K	Innovatrics	2009	0.05	1.17
MX2-IV-L	Innovatrics	2009	0.05	1.34
MX2-IV-M	Micro-PackS	2009	0.04	0.54
MX2-IV-N	Dermalog	2009	0.05	0.38
MX2-IV-O	Dermalog	2009	0.05	0.61
MX2-IV-P	Dermalog	2009	0.05	0.72
MX2-IV-Q	IIR	2009	0.08	1.01

Figure 5: Evolution of MATCH-ON-CARD speed and accuracy over the three MINEX II phases. The circles show a single (FNMR ,Duration) datapoint for each MINEX II algorithms. That is FNMR at FMR = 0.001 for single finger genuine comparisons is plotted against median duration of the comparison. The duration is defined as the measured ISO/IEC 7816 VERIFY time. Both scales are logarithmic. The reference templates and authentication templates were produced by B (Table 6) and MX2D (Table 1) respectively. This pair is adopted for this figure because it was used in all MINEX II phases. The raw data is shown at right.

▷ **Institute for Infocomm Research:** The Phase IV algorithm is the first submitted to MINEX II .

▷ **Cogent:** No algorithms were tested in Phase IV. The Phase III algorithm remains competitive on accuracy

MX2-IV-A = Neurotechnology-Athena	MX2-IV-B = Neurotechnology-Athena	MX2-IV-C = Morpho-Morpho	MX2-IV-D = Morpho-Morpho
MX2-IV-E = ID3-Oberthur	MX2-IV-F = ID3-Oberthur	MX2-IV-G = Precise Biometrics-Spyrus	MX2-IV-H = Precise Biometrics-G+D
MX2-IV-I = Precise Biometrics-Gemalto	MX2-IV-J = Precise Biometrics-Gemalto	MX2-IV-K = Innovatrics-Gemalto	MX2-IV-L = Innovatrics-Gemalto
MX2-IV-M = Micro-PackS-Gemalto	MX2-IV-N = Dermalog-Gemalto	MX2-IV-O = Dermalog-PAV Card	MX2-IV-P = Dermalog-MaskTech
MX2-IV-Q = Inst Infocomm Rsrch-DART			

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A Open-source support for MOC

MINEX II demonstrated an unprecedented level of openness in its evaluation methods. Specifically the test plan was developed in conjunction with industry and both the template conversion and MATCH-ON-CARD test harness were fully open during their development phase, as decribed below.

A.1 Support for biometric data interchange standards

The BIOMDI open source project[17] contains several software library and program packages for handling records specified in INCITS and ISO biometric data format standards. The MINEX II test program uses the finger minutia package to process the INCITS 378 records, converting them to ISO compact card format. In addition, several tools in this package are used to validate the records, or simply to view them.

A.2 Support for MATCH-ON-CARD implementations

The BIOMAPP open source project[18] contains the source code for the match on card test drivers, the tag-length-value (TLV) object processing, and an example SDK test driver. The programs within the BIOMAPP project make use of the finger minutiae libraries from the BIOMDI project. Also, the card test driver utilizes the pcsclite library described in Appendix B.

The goal of the BIOMAPP match on card package is to achieve independence from any particular vendor's middleware. The software communicates directly with the card at the APDU level, removing any need for a middleware API or custom smart card software.

B Hardware used

The testing software used on the NIST test systems is comprised of several layers: The NIST test driver; the PC/SC library; the PC/SC daemon; and the USB device drivers. The NIST test driver is part of the BIOMAPP project, described above. The operating system used was RedHat Enterprise Linux 4.

The PC/SC software used is part of the M.U.S.C.L.E. (www.linuxnet.com) project developing smartcard solutions for the Linux, OS-X, and Solaris operating systems. Many Linux distributions include the pcsclite package, comprising the PC/SC library and daemon. The smartcard reader driver used was the generic CCID driver. We initially used version 1.3.7 of the pcsc-lite driver (the default under Redhat 5) but migrated to version 1.4.0 after it was found that the older version added a nearly constant delay to all APDU calls. The newer version was used for all times reported herein.

Testing was done on dual-CPU Intel Xeon based blade computers, running at 2.80 GHz. Each system has 2G of RAM. The smartcard reader is the SCR 335 produced by SCM Microsystems, with a USB interface, and is CCID compliant. This reader supports T=0 and T=1 protocols, 7816 Class A and AB cards, up to 8 MHz.

Note that in Phase III (2009) the PC/SC library had upgraded from version 1.4.0 to 1.5.2 because the operating system had been updated, Redhat 5 vs. 4. While, the hardware was identical throughout, the time for all operations increased by about 0.005 seconds. We consider that this kind of systematic error will be an operational reality unless specific regression tests are performed after an update.

C Audit information

Study	MINEX II PHASE II
Report generated	Tue Mar 15 14:50:39 2011
Report name	minex_report.tex
Report last modified	Tue Mar 15 08:42:36 2011
Report MD5 hexadecimal	9e992479eb53334179d8a7bfae557fb2
NIST contact	minexII@nist.gov

[17] See http://biometrics.nist.gov/nigos
[18] Ibid.