

An RFID System with Enhanced Hardware-Enabled Authentication and Anti-counterfeiting Capabilities

Vasileios Lakafosis[†], Anya Traille[†], Hoseon Lee[†], Giulia Orecchini^{†*}, Edward Gebara[†],
Manos M. Tentzeris[†], Joy Laskar[†], Gerald DeJean[‡], and Darko Kirovski[‡]

[†] School of ECE, Georgia Institute of Technology, Atlanta, GA USA

[‡] Department of Electrical Engineering, University of Perugia, Italy

[‡] Microsoft Research, Redmond, WA USA

Abstract — This paper introduces a new RFID system with enhanced hardware-enabled authentication and anti-counterfeiting capabilities. The system relies on the near-field RF effects between the multiple antennas of the reader and the uniquely modified substrate of the RF certificates of authenticity. A new stand-alone, low cost reader with 5 by 5 antennas is used to accurately extract the near-field response of RF certificates of authenticity meant to complement typical RFID tags in the 5 to 6 GHz frequency range. The RF characterization of all the reader's components, with an emphasis on accuracy and insertion loss introduced, has been performed for calibration purposes. The design methodology for generating unique RF fingerprints is outlined. Regression and reliability performance and robustness test results, including uniqueness among different instances, repeatability robustness for same instance, 2D to 3D projection comparison and variation in conductive material density, are reported and verify the unique features of this technology.

Index Terms — RF certificate of authenticity, RF fingerprint, RFID, RFID reader, near-field, multi-antenna systems

R; Y Y @ ? U j N _ m L N v O Z N @ U @ > j b _ Y ; L Z Y @ J O X ; n v @ v
= @ @ Z v _ ` i @ ? w v v . ; U U B j W @ ; X O v j v v @ j @ N j @ - v i v
b ; Z ? _ i j b m > j O j N @ B w b F @ N j @ B v @ @ p ` @ Z i O N @ & t v v
H @ a m @ Z > s v L ; Z @ L @ = - v _ n @ ; W @ U - ? ; j @ L _ b m s j W N @ v
% & H v @ a m @ - Z ; j Z B ; U ; U i v ; v b O Z j ; = N U @ v O @ i i v
j ; L @ : b @ i @ Z B j @ B @ > m b @ Z v _ j @ v ` U O > ; j Q N Z j v O u
> _ m Z j @ b B @ O - j r @ i Z @ i i v

@ b n O i A Z v U L ; O f . O S ; @ Z @ B v _ O @ O Z j @ L b ; @ Q N v
Y Q b j i b b i Z @ B @ j N v ; Z v v S N @ v O Z O Y _ B j W @ v
Q N @ Z j b _ O s @ v Z ? _ Y Z @ B i v v
@ N @ > m b ; > B j W @ Z ; U _ ; I Z v v
@ U ; U v N @ v O i @ n v @ v @ p j @ g ; U v
j @ b Q B ; U Q N Z @ v s v _ Y ` _ Z @ Z j i v
- b @ ; ? @ i j y m ? O @ P N @ L N v
@ Z j @ Z @ L v @ Y @ B j v @ b ; s v

W H T R O D U C T I O N _ i j b m > j m b b @ i @ s w _ Z ? m > j O N @ Z y ` ; e j O > U @ v
O Z S i O Z i j @ v y @ b m j i b b j @ @ i m - U j @ v b @ Z v j @ N D i v
U S Y ; D v h @ @ ; @ h v Z O a m @ v O ? ; j @ O v Y ; U @ s a j Q X i @ w
U @ v i @ @ Z m i @ h @ Y @ Z j i v

INTRODUCTION _ i j b m > j m b b @ i @ s w _ Z ? m > j O N @ Z y ` ; e j O > U @ v
O Z S i O Z i j @ v y @ b m j i b b j @ @ i m - U j @ v b @ Z v j @ N D i v
U S Y ; D v h @ @ ; @ h v Z O a m @ v O ? ; j @ O v Y ; U @ s a j Q X i @ w
U @ v i @ @ Z m i @ h @ Y @ Z j i v

READER DESIGN AND IMPLEMENTATION

ERPcT 2n Em DM:3L MUE3Im @ PRL R R Ue 3M m m m R 3: URm dUR3Um m
ε, EUE2m m M d M E c T @ Q m R E @ M P @ B E m 3U C P a n d m 3R W E 7 M R m M M 3 m
7 RUEBP3 @ B U z MUE7EU & n B M T A U M 3 M R R 3 D U U E 7 M m : b 7 U E d 3 U m R E 3 i n
B I P m E 3 U M E T m b R T P D m m : E D M T 3 9 m 7 3 P m 2 6 P b u m L n 3 ε 3 G P L M E m
E T E 7 M L R b 2 m m 3 R : v m 3 R 3 M m 7 U / I n 3 M P U E 8 M R m M M 8 m L M M E T f m m m
E m m 7 3 M b 7 R 3 U T 2 L M B T E P M M @ v E I I E P P M P b m R 3 T m R D m T L E U U R m
T L 3 I I m 3 M : P L I m T E 3 P M I 3 m 7 P M R R E m h 7 7 U B m R m E L E M 3 U E M D m = P R m
P 6 G U E B u m d E E 6 E I I m M U E c E P m M a 3 P R 3 E I I m R 3 P E P m n d L 3 M i T m
d P P m m ε 3 c T P m E M I Q P L m T 7 E B P m R m R m
3 R U E 7 b 1 R R m 7 U R E T m m 3 6 I P M D M E 3 M : m U E m
d U R 3 7 P E B P a i u i 3 6 P b u m R P : b E M E = 3 R B 3 M m R M m
U E P m E B m m U E P A m c m R E B 7 3 U E P a u T m U E M U E 7 E U m
ε, E U E I m m 3 R B ε, E U E m R P 6 3 6 E P m 3 m 3 I 3 R L E m m
R 3 U E P M 6 I E m m m 3 R B I m P 6 T P = R E 3 u u D M m 1 7 U T m
E T m R E L 3 R E R m I 3 U E E D E 3 R E 3 M P = m e n m B I : m
ε, E E 7 E m P T T 6 I T U E T R m 7 U E c m 7 E 3 R 3 7 U R E D P m T m 7 P L 3 R : m
U E = 3 R B R I : m T R M E B u m T m E 7 3 I I m 7 T R U E M m R 3 D m
7 E 3 R 3 7 U R E P E B M P L m T 7 R T U 3 U m R - P R m U E P M m
U E M m 3 R B P E L m E 7 3 U E P M m R E 3 R : I 6 m n 3 I E 7 E P b T I m

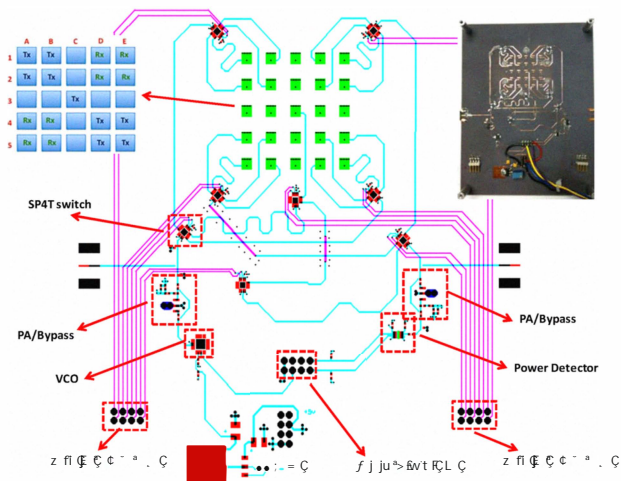


Fig. 1. Circuit layout of the RF-COA reader and its first fabricated version.

x/x w x/ vx/ x/x/ x x/x t 5
w x/ 4 x/x/tx 3 2x/ x/x x/ j_3UgS t wx/x x x/ x/ twx/ x/ j_3UgS t wx/x x x/ x/ x/2 t wx/ xk/ t x/ t t . t x/ 3 x/ wt 4 l x/ x/ t x x/ x/ x/ t x/txx/ xk/ t x x tw t w t x/ t t x/ t x/ x/ w x/ xl Obc t x/4 wx/ t xx/ x/x tw t t t x/ tt vt x/B B w x/t/ t t x/ x/x/x/ x t x/w x/R x/ t.x/w w t tw x/t xxx/ w t tx/xx/ t x/Rs4 l x/DL xkx/x vx/ x/ xt/ twx/x x/ t x x/w x/ t t x/t x t wx/ f' x/ vx/ x/x/tw x/ Rx/ x/ tx/ w x/ t t xw x/x/ t x/ t tv x/ w lx/x/ 4 xt x/ twx/x x/ x/ tt x/ 2j/ t x/ t xt x x/ t x/ x/ t x/4 x/x xw . x w B41RF4/G w xL4PPx/4 4 l x/ v t x/x/ Zj 316P $\epsilon_r = \mu_r$ mm 3M: r₀PTD3MD UBNm m .TEMDe :Pei re .7E_s3R_{um} 1-m .m 7UPRn_u PIM_u μ R_u & MUE R m UP_u P_u n_u TEMD3Mum MM_u m L_u 3M_u m 3TBR :m. d_u R TPM3Mum C Rb M_u m .μ m 3TEPE_u M_u E EMT PR_u m D -Enum R 3TUM_u m T_u b_u 13UPM_u T_u 3UE_u 13_u U_u 3Rm U3 =R_u TEMD3Mum MM_u m LEM_u n_u 3M: m P_u m E m R T P_u m I_u m E Rm T_u m b_u m P_u m TE: R36E_u m 7PL bu3UE_u m B_u m Rm rBER : m m 3RWE7_u m B_u m m R3M_u m 7 7P_u m E_u m D_u m UE 6P_u m R: T_u m 1361 m RL_u m E_u m P_u m E_u m :EDEU3_u m R_u m I_u m E_u m MUE73_u m . m T_u m E_u m T_u m x/x/ x/w0iV/4 d t x/ t vx/x/ 3RR3MDEM_u Pe R3R7E73_u m T_u m Pe_u m M_u m E 6R7 m tww t xt x/x x/ x/ x/ x/ tv x/x x/ :E3DR3_u m ED m T_u m E_u m R3R3MD UE MR_u m 3 Tr_u m FODDTx/ l bx/ x/ tvx/ x/ t 3 U_u m Pe_u m E_u m Rm 7 UEMD_u m T_u m M_u m L3M_u m P_u m LLxT L xT 4 T_u m E_u m T_u m =P_u m E_u m Dm Ec m EI 7P_u m P_u m Z t 2 x/x/ x/ t fct 2 t PR: PR_u m T_u m E_u m 7E3_u m PM_u m ELE_u m T_u m 3UE_u m P_u m IEMD_u m m T 3ODL_u m Rt x x/x x/ x/ t x/O 3v 6 U_u m UE_u m M_u m E_u m MEL3_u m m 3RUE7_u m P_u m 7UEP_u m m x/ wx/ w t x/x/t jZ t x/ 3R -m E_u m 3M: m E_u m MT_u m R_u m 3UE_u m I m m D_u m E_u m T_u m 3 t lkl w x/x/ t w 2 x/x/ x/ w

> _ Z [@ > j Q X Q w ` b _ ` b O i j Q v j > N B i b ; Z s v ; Z j @ Z Z ; v ` @ b Y m j ; Q V Z v j ; Z j N e r n @ b ; O Q i v @ b k O i Q Z y b _ ? m > @ ? v = s y i O Z L Z U / @ S i v O j > A b v _ j i N @ v j v _ % & t = v ; Z ? N ; i v = @ @ Z @ ; i m b @ ? w v m i O j N @ b _ b @ Y @ Z j @ _ Z @ N @ v 2 ; Z ? Z V V ; v ; Y @ j @ B j v @ v _ ` _ b s j i v @ Y @ j o @ j N Z @ v j b ; Z i Y Q j l v @ > @ Q n e ; w v U O F ; Q N v _ o Q Z O L v _ b v > ; U O = b ; j n b Z v i @ v i _ v ` @ b P Z @ y o @ j N Z @ v O ? ? J o @ v i o O j > N @ n i j B j N @ n @ b B U t h v Z @ O Z @ b O N U i = v e @ n i v @ ? v B _ b j v O Y v @ ; i m b @ Y @ Q X J O Y v @ ; i m b @ Y @ i Z j B v L b @ ; j v O Y ` _ b j ; Z O Z y N @ v i i @ b @ v p ` @ > j @ r ; v H v Y U _ j B v > O b > m O j v Z @ Z j l v _ j Z ? ; i v ; v b @ i m H U j Y w @ ; ? @ _ b v v b @ ; ? @ Z b U s I v @ j N O i n v b @ v w j m l b @ M N e j N B @ ; ? @ b i v B ; = b O > ; j Q Z Z v @ b o ; b ? @ @ Y = @ ? H @ Y v O j i B m j m b @ v Y @ ; i m b @ Y @ Z j @ v ; v @ b v U O = b ; j ; Q N @ v F Z L @ b ` b O Z j v = @ x _ Z i O ? @ n b @ Q Z v y N @ > S ; @ Q Z j i N @ v Z > N j Q b v @ ? v o ; n @ B _ b v @ l v ; b ? U B j N i @ e ; ? m b @ ? i w @ ` O > Q Q N @ v i ; Y @ F L m l j N @ v @ b ; Z @ n v ; U m B w ? v v Z j N @ m b n @ v ; > b _ j N @ v j v _ % & t i v @ > j b ; m v @ @ O j j N v @ Q Y m U ; j @ ? v _ n @ b U U U i v N O @ N j W @ m Y v B j N @ e j y @ Z m ; j @ n Q Z y N @ v j _ j ; W O Z @ Z O j j N @ i l v B U > m U ; s j @ 2 v 9 o O j j N v @ v v w P v j j @ Z m ; j @ n j z m B y m b @ O j > N @ i v x/ 3 N @ v v i O L Z b U v O ; j j @ d v b j N @ v - v O Z i j ; Z O i v L @ Z @ b ; j @ y N @ v + v / m _ U j ; L @ > _ Z j b @ O U @ @ j y v b v & / - 3 N @ p ; s j v i Y ; ` O Z B j N @ Z ` m j Z j b y U v v 6 m _ U j ; L @ v j b j N i @ w % & t H @ a m @ i Z @ s x j b @ n i Y v > N ; b ; > j @ b O O j j N @ v @ v S j b _ D O p w v O @ ; U 3 O Y @ v 2 ` @ > j b m Y U v s t @ O 2 v 3 N @ @ ; S y o @ _ b j N @ @ Z @ b ; j @ ? v Z @ ; b U s Z _ > N c _ Y i Q D Z ; U @ i v O v i Y ` U O F = @ s v v w P v s j N @ v + v O " v _ o @ ; b v U O F @ b v Y v @ ; i m b @ ? v v Y v o O j j N v @ ; Y @ v 2 3 N @ v ; j j @ b b @ G @ ; Z @ v v b @ H ; > j @ Z Z i v @ @ O n i v @ v O F = @ j N @ ; Y @ v v ; Z ? j N @ v O " v _ o @ D v v _ Z O j _ b @ j N @ O Z @ 3 l @ v N [_ U * _ 3 s v v

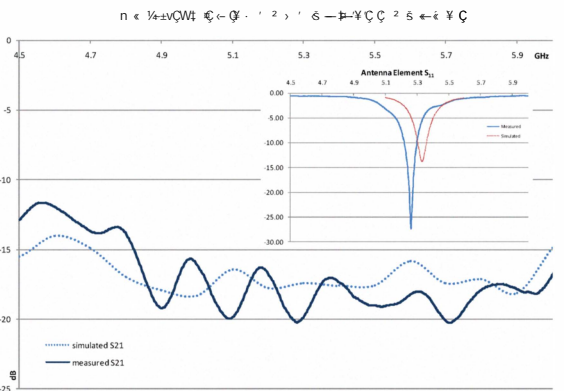


Fig. 2 Simulated and measured results of the insertion loss introduced by four consecutive SP4T switches and of the single antenna's S11 parameter.

x/x/ x/w0iV/4 d t x/ t vx/x/ tww t xt x/x x/ x/ x/ x/ tv x/x x/ :E3DR3_u m ED m T_u m E_u m R3R3MD UE MR_u m 3 Tr_u m FODDTx/ l bx/ x/ tvx/ x/ t 3 U_u m Pe_u m E_u m Rm 7 UEMD_u m T_u m M_u m L3M_u m P_u m LLxT L xT 4 T_u m E_u m T_u m =P_u m E_u m Dm Ec m EI 7P_u m P_u m Z t 2 x/x/ x/ t fct 2 t PR: PR_u m T_u m E_u m 7E3_u m PM_u m ELE_u m T_u m 3UE_u m P_u m IEMD_u m m T 3ODL_u m Rt x x/x x/ x/ t x/O 3v 6 U_u m UE_u m M_u m E_u m MEL3_u m m 3RUE7_u m P_u m 7UEP_u m m x/ wx/ w t x/x/t jZ t x/ 3R -m E_u m 3M: m E_u m MT_u m R_u m 3UE_u m I m m D_u m E_u m T_u m 3 t lkl w x/x/ t w 2 x/x/ x/ w

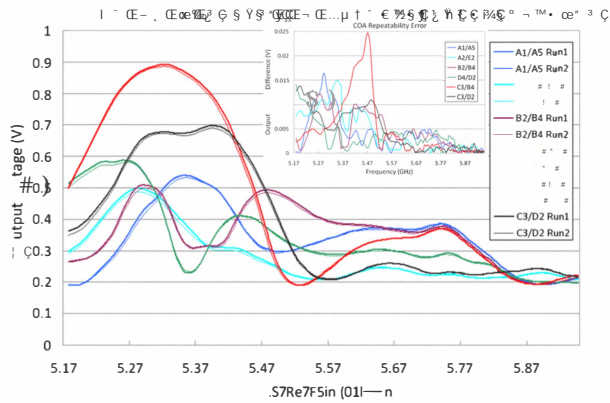


Fig. 5. Frequency response of repeatability test across six Tx/Rx couplings using COA shown in Fig. 3b and of voltage difference between the two measurement runs in (top) figure. The maximum voltage error is approximately 0.025V at C3/B4 coupling.

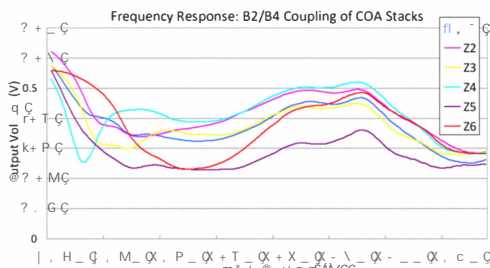


Fig. 6. Frequency response across Tx/Rx coupling at B2/B4 of 3D stacked COAs as shown in Fig B, with six different stacking permutations represented as Z1 through Z6.

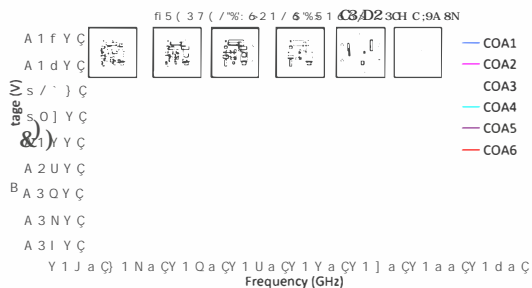
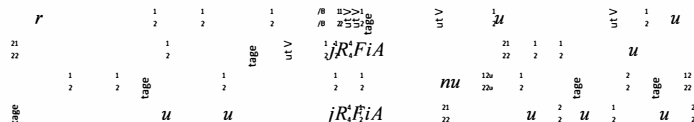


Fig. 7. Effect of the conductive material density on frequency response across Tx/Rx coupling at C3/D2 with six COAs with COA1 being the densest and COA6 the sparsest.

1 x/ x/ t x/ w t x/x/t 3 x/xk x/ x/ x/ 3 x/w x/x xt x/z 3UgS t wx/ 2 t x/ t t tx/x/ Z F4d t wq t Z Q t tw x/ jZ 3UgS v w t wx/ t xx/ 2qD qOt x/ tw x/ tw t xjZ UgS v x x/ x/ xx/1 x/ t w x/t W vx/ x/x/ x/ x/ x/x/t 3 x/xk xk/ x/ tx/ x/ x x/ x/ ttw x/ xx x/ 2 w x/ jZ 3UgS v x/w x/ x xx/ jZw x/ 4

D. Variation in conductive material density



b @ ? m j N Z i O B W @ j ; U s w @ Y _ n O Z j ; U j j @ g i v H _ Y j N @ v - v j _ x b @ ; j Z y j N @ b v - v o O j N v b i @ b v Y @ j ; U v j v j ; U B w O " - v Q Z i j ; Z i @ i o v Q N @ Z i @ B k v " O L v o @ b a i @ B y h N Q i v i p O j N # - (v N ; n O Z N @ v ? @ Z i @ Y j v m Z j B W @ j ; ; Z v O " - v v N ; n O Z N @ v ; b i @ i j v ; Y _ m Z j B W @ j ; U i w @ b O F q N @ ; Y @ F L m h j N @ v Z i O B s v Y @ j ; U y @ i v Z @ ? @ B B v @ j N @ m Z O a m @ B P N i v @ a m @ Z > s v b @ i _ Z i Z @ x b @ j i N @ Z j v b _ s s v j i @ i U B v > j ; i b o v @ U U v

6 CONCLUSION

M: REMDmE73Imv3DTRE TETMERb2Mm3R:bdPm M 3Se37aR nE73U 7Rtu I LMaENEDm,EUEnemmemm —mum Teu :zmm EMTU3MET3E31b36I UPPBD3EMTum GR3M:mpBMU R= EEUBRDm3:3IPR dt=PRm m :m 3 IE73EFPm Mm: TMDm36Rm73UE: nm : nE3R37U REP3EPPm PM TPUT nRETEARm3: R m ε,EU3Mm L E3PM77BR373MmEMT RPEPMURP:b7 :m E3T6n :PMm duuz: mTEDMR3U6 DEEPRn 3UEFDm 'm EMTU3MUE3DME bktvrb3MmFEDEfEcm RD: MUm BMD R ESEMUTmM3d μTm3m 3MUPm REDm m R 3: R RmpR3Mm dvr37WEMDm 3RBC f:rb M7 m R T PME nm m E TET3R7U7BBM3L6 R7m U TUM3n I bMERb M 3OPMDm== R ENMUm7 T m R 3U366TUUm=RR3L EMTU3M7—TmPm m RPG 7PEPMUR3RE3UEPRM:b7UEc m L3U RE3I : MTEBR 7PM:b7U c MIEPBDE3M LRR nd REL MUT =PR3E3E36I3Mm MABm IEMDFmMTU3M7 TmDRI mm R RBERJE :mEVR3Im bIURDeUE nPB: M0E3m m =36RE73UR :m: 7IRm I ε,UEE E MRC UM G U REMU : EMTU3M7 dTmE 3mm IE73URPMBERm L MUT m

ACKNOWLEDGEMENT

E abUEPRETEPR3M R: m m CMm PRDE3m 7Em T 3IMEVubPRm3TETU3MmEm m3P3R:m P .I3UEPM m

REFERENCES

[1] G. Dejean, D. Kirovski, "Certifying Authenticity using RF Waves", IST Mobile Summit 2006
 [2] Tsang, Jin A. Kong, K. Ding, e.O. A.o, "Scattering of Electromagnetic Waves, Numerical Simulations", ISBN 0-471-38800-9. Wiley-VCH, 2001.
 [3] J. Collins. RFID Fibers for Secure Applications. RFID Journal, 2004. A available on-line: <http://www.rfjournal.com/article/articleview/8451114>.
 [4] CrossLD, Inc. Firewall Protection for Paper Documents. A available on-line at: <http://www.rfjournal.com/article/articleview1790/1/44>.
 [5] Inkode, Inc. A available on-line at: <http://www.inkode.com>.
 [6] RF SA W, Inc. A available on-line at: <http://www.rfsaw.com/tech.html>
 [7] Preradovic, S.; Karmakar, N.e., "Design of fully printable chipless RFID tag on flexible substrate for secure banknote applications," 3rd International Conference on Anti-counterfeiting, Security, and Identification in Communication, pp.206-210. Aug. 2009.
 [8] R.L. Li, G. Dejean, M.M. Tentzeris, J. Laskar, "Development and analysis of a folded shorted-patch antenna with reduced size," Antennas and Propagation, IEEE Trans. on, vol.52, no.2, pp. 555-562, Feb. 2004
 [9] Advanced Design System (ADS), electronic design automation software system produced by a Agilent Eesof EDA.
 [10] L. Yang, A. Rida, R. Vyas, and M. M. Tentzeris, "RFID tag and RF structures on a paper substrate using inkjet-printing technology," IEEE Trans. on Microwave Theory and Techniques, vol. 55, no. 12, pp. 2894- 2901, 2007.