EUROPEAN COMMISSION

Community Research

PHYLAWS

SEVENTH FRAMEWORK PROGRAMME

ICT Call 8

PHYsical LAyer Wireless Security

Physical layer security based protocols to effectively secure wireless communications without key distribution

WinnComm Europe 2015

Erlangen – 10/07/2015

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- INTRODUCTION
- INTEREST OF PHYSEC
- SECRET KEY GENERATION
- ARTIFICIAL NOISE
- SECRECY CODING
- CONCLUSION

- **LACKS OF SECURITY IN EXISTING WIDESPREAD WIRELESS NETWORKS**
  - **Mobile Telephony**

    Using failures of the SS7 and international roaming protocols to get Ki keys

    - Monitoring of VIP's smartphone during years
    - Security of subscribers can be decreased by networks protocol weaknesses

    SIM card providers may be hacked

    - Hacking of SIM manufacturers by security agencies to obtain Ki Keys
    - Subscribers' keys may not be secret in practice

  - **WiFi**

    Where's security in WiFi ? An Argument for Industry Awareness

    - Use of WEP keys
    - WPS enables to crack WPA-2

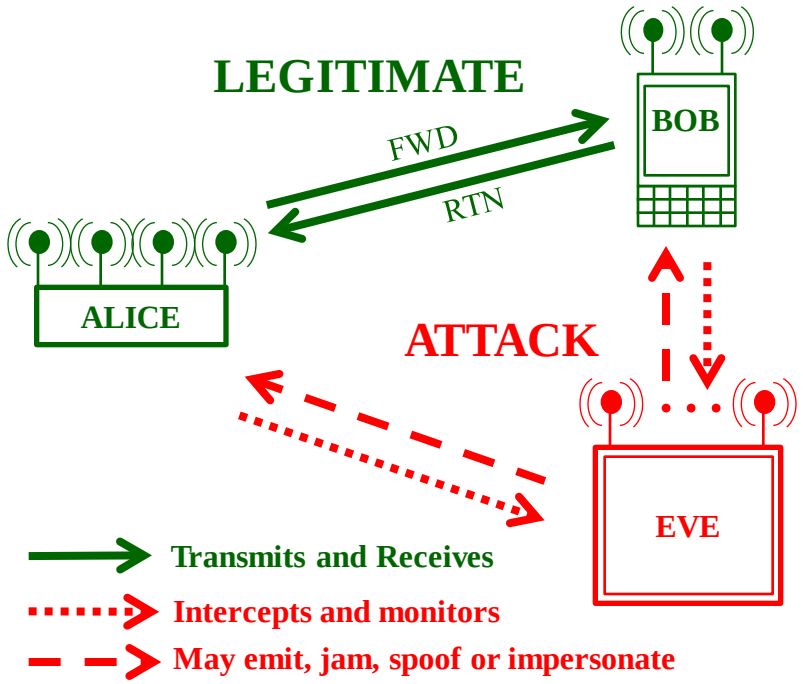
  - **Internet of Things**

    FBI: "Internet of Things poses opportunities for cyber crime"

    - Weak security control
    - Vulnerability of the air interface

COMMUNICATION SCENARIO

- **LEGITIMATE** links are Alice to/from Bob
- **EAVESDROPPER** links are
  - Alice to Eve…and even (active) Eve to Alice
  - Bob to Eve… and even (active) Eve to Bob
- Most usual academic hypothesis are:
  - complete information of Eve about legitimate RATs/waveforms
  - no Information of Eve about legitimate Keys (e.g. Ki Keys on SIM cards)
  - No more valid nowadays in public RATs



CLASSIC SECURITY COUNTERMEASURES

- TRANSEC (Transmission Security) is the protection of the transmitted signals face to interception and intrusion attempts (and even jamming and direction finding)
- NETSEC (Network Transmission Security) is the protection of signalling and access messages. Usual solutions are authentication and integrity control (or ciphering of signalling in military networks)
- COMSEC (Communication Security) is the protection of data messages (voice, sms, mms, high speed data). Most of solutions are based on ciphering and integrity control schemes

- **NEW ADD-ON SECURITY SCHEMES SHALL**
  - Not rely on pre-distribution of keys
  - Be compatible with a large numbers of subscribers
  - Be easy to implement and standard compliant
  - Be efficient against any kind of attack

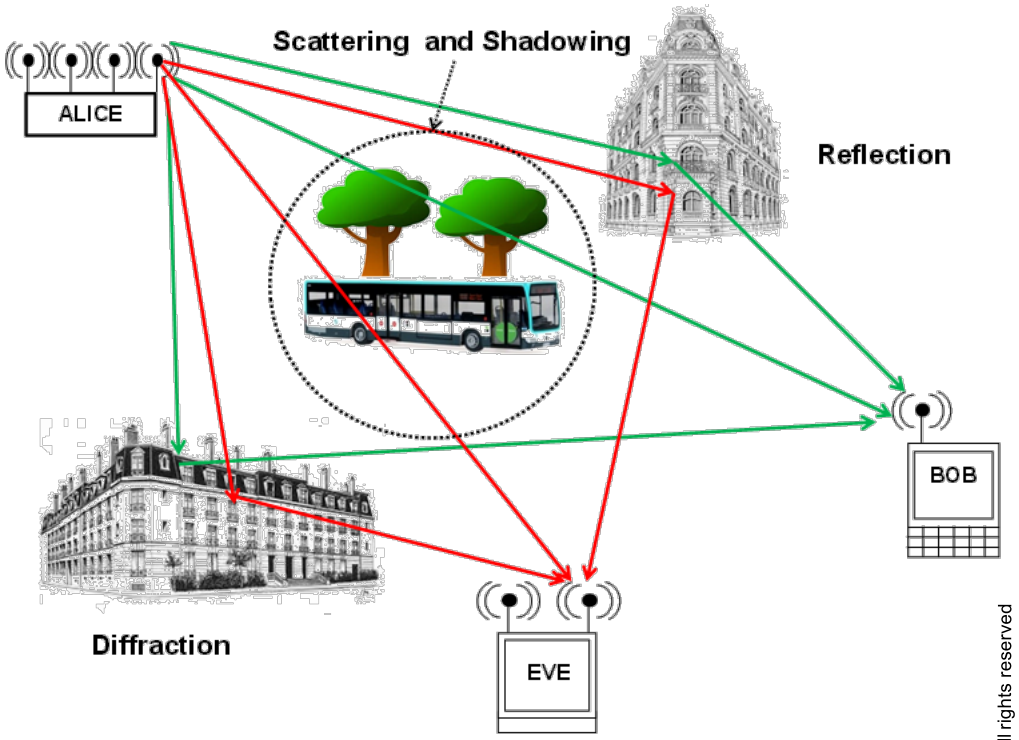
- **EMERGENCE OF A NEW SECURITY TECHNIQUE: "PHYSICAL LAYER SECURITY"**
  - PHYSEC
  - Key-less security technique exploiting propagation randomness to establish secrecy between legitimate users
  - Theories are well developed and results are promising
  - Practical implementations are thriving
  - Various techniques for different kinds of protection
  - Adaptive techniques

EXPLOITING THE RANDOM PROPAGATION OF WIRELESS RADIO CHANNEL

- **Obstacles between users**
  - Multiple paths to reach Bob or Eve
    - Reflection, Diffraction, Scattering, Shadowing
  - Waveforms received by Bob and Eve are differently altered
  - Apply both to outdoor and indoor

- **Complex propagation and unpredictable scattering objects**
  - Channel randomness
  - Received waveforms cannot be recovered by computation

- **At fixed carrier, same angles on obstacles for Alice → Bob and Bob → Alice**
  - Channel reciprocity (in TDD)
  - Same randomness for Alice and Bob
  - Decorrelation for Eve after short distances
    - λ/2 in dense environment
    - 4 λ in low diversity environment



PHYSEC: Key-less security technique exploiting propagation randomness to establish secrecy

- **2 MAIN APPROACHES FOR PHYSEC**
  - **Secret Key Generation (SKG): Secret Keys are computed from channel measurements**
    - **Channels between legitimate nodes are reciprocal and uncorrelated elsewhere**
    - **Propagation randomness ensures the uniqueness of the computed key**

  Channel quantization algorithms target low mismatches between legitimate links

  Existing SKG strategies ensure few information leakage to third parties

- *Y. El Hajj et al., "Towards robust key extraction from multipath wireless channels", IEEE Journal of Comm. and Net., vol.14, no.4, 2012*
- *www-phylaws.ict.org, deliverable D4.1*

  - **Secrecy codes: channel codes (FEC) are augmented with secrecy capabilities**
    - **Require better radio link (SNR) between Alice and Bob than between Alice and Eve**
    - **Approach Shannon capacity for legitimate link**
    - **Mitigate information leakage at "any" other location**

  Theoretical feasibility is established but explicit design remains an active research domain

  Expected results from Phylaws project in 2016

- *Bloch and Barros, "Physical Layer security", Cambridge University Press, 2011*

AUTHENTICATION OF THE RADIO LINK

- Tag Signals and Interrogation and Acknowledgement Sequences
- See previous presentation at WinnComm 2015 (San Diego)

Towards a key-free radio protocol for authentication and security of nodes and terminals in advanced waveforms

SDR'15 Winncomm, session 1, San Diego, 26 March 2015

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Supported by PHYLAWS project FP7 ICT Id-317562

PROVIDING A RADIO-ADVANTAGE FOR THE LEGITIMATE LINK

- Artificial Noise (AN): Beamforming for legitimate data stream
  - Extraction of orthogonal directions to the legitimate link and transmission of noise streams
  - Maximization of the legitimate link budget providing a radio advantage for the legitimate link

Theories and implementations are numerous, practical performance is proven for WiFi

- *S. Goel and R. Negi,"Guaranteeing Secrecy using Artificial Noise", IEEE Transaction on Wireless Communications, vol.7, no.6, June 2008*
- *www-phylaws.ict.org, deliverable D2.4*

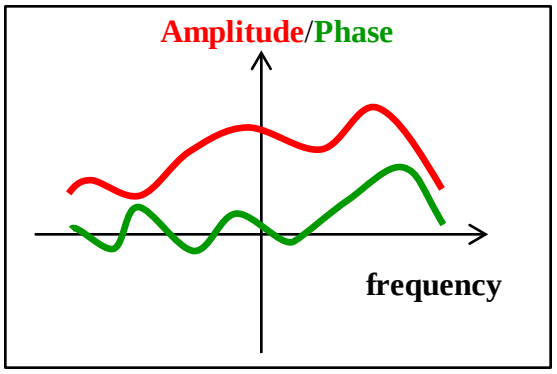
- Tag signals and Interrogation and Acknowledgement Sequences

PRINCIPLE OF SECRET KEY GENERATION

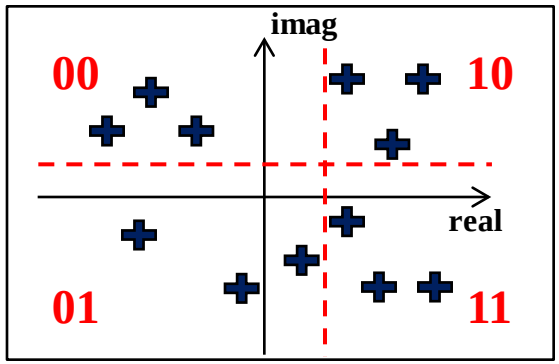
- The goal is to use channel randomness to extract secret keys
- Keys computed by legitimate users shall be exactly the same
- Keys computed by eavesdroppers shall be indepedent from the secret key

SIMPLIFIED GENERATION PROCESS OF SECRET KEYS

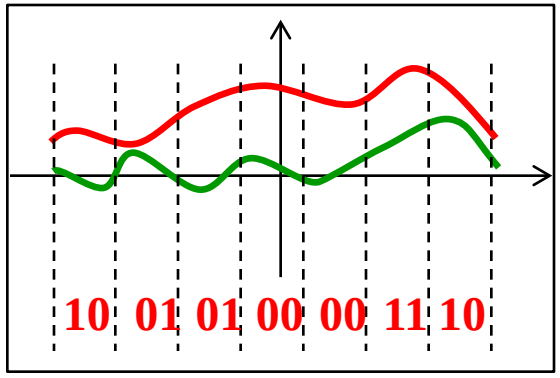
- Step 1: Estimation of the Channel Frequency Response (CFR)
  - Study of the correlation of the CFR
- Step 2: Quantization
  - channel coefficients are quantized according to a defined and public algorithm
- Step 3: Information reconciliation
  - Alice and Bob use error-correcting code (BCH) on the obtained key to suppress mismatch
- Step 4: Privacy amplification
  - Alice and Bob use hash functions to strengthen the quality of their key



- Estimation of the Channel Frequency Response (CFR)



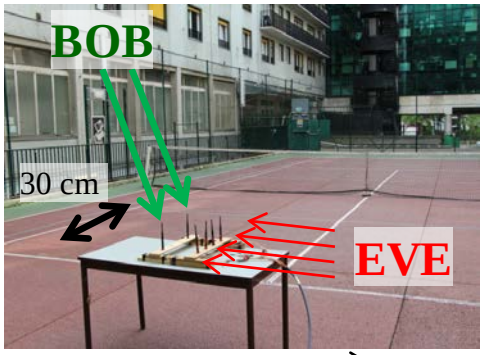
- Quantization and study of repartition of the points



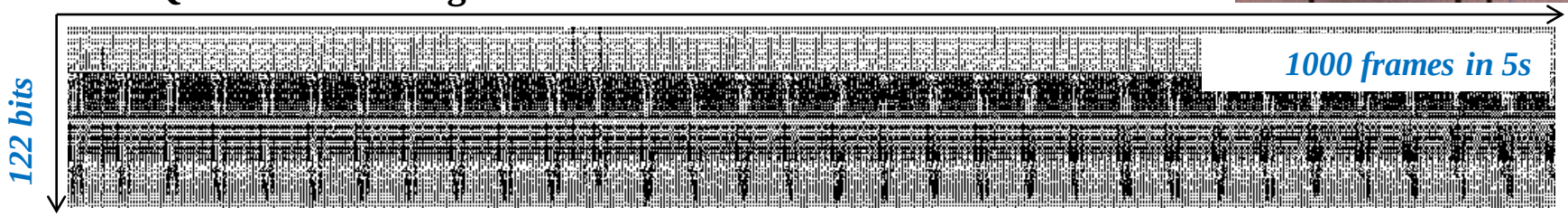
- Each quantized point is then translated into bits

- **FIRST CHALLENGE: CHANNEL CORRELATION**
  - **Occurs in environnement with low mobility, resulting in:**
    - **Stability in channel response, longer coherence time and not enough randomness in secret keys**
  - **How to reduce channel correlation before quantization to improve quality of the keys?**
- **STRAIGHTFORWARD METHOD TO REMOVE TEMPORAL CORRELATION**
  - **Use of the eigenvector of the full covariance matrix of the channel response. However:**
    - **High complexity and Bob has to send the eigenvectors to Alice over the public channel**
  - Chan Chen; Jensen, M.A., "Secret Key Establishment Using Temporally and Spatially Correlated Wireless Channel Coefficients," Mobile Computing, IEEE Transactions on , vol.10, no.2, pp.205,215, Feb. 2011
- **TOWARDS A LESS COMPLEX SOLUTION: A FIRST APPROACH**
  - **Remove time correlation between frames**
    - **Compute cross-correlation coefficient between two consecutive frames**
    - **Select only frames for which the cross-correlation coefficient is above a given threshold T_t**
  - **Remove correlation between frequency carriers**
    - **Compute cross-correlation between two consecutive frames**
    - **Select only frequencies for which the cross-correlation coefficient is above a given threshold T_f**
  - **Bob has to send the position of the selected channel coefficients to Alice**
    - **Does not leak any information about the key to Eve**

IMPACT OF CHANNEL DECORRELATION



- Worst case = LTE measurements in a stationnary environment
  - Frequency: 2627.5MHz , Bandwidth: 10 MHz
  - Acquisition duration: 5 seconds
  - 6 antennas : 2 for Bob, 4 for Eve
- Quantization using all available channel coefficients

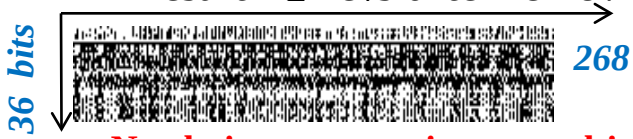


High temporal correlation that can be exploited by Eve to recover Bob's key

- Resulting keys after using the eigenvectors of the channel covariance matrix

The correlation problem persists

- Resulting keys after removing highly correlated frames with the low complex method

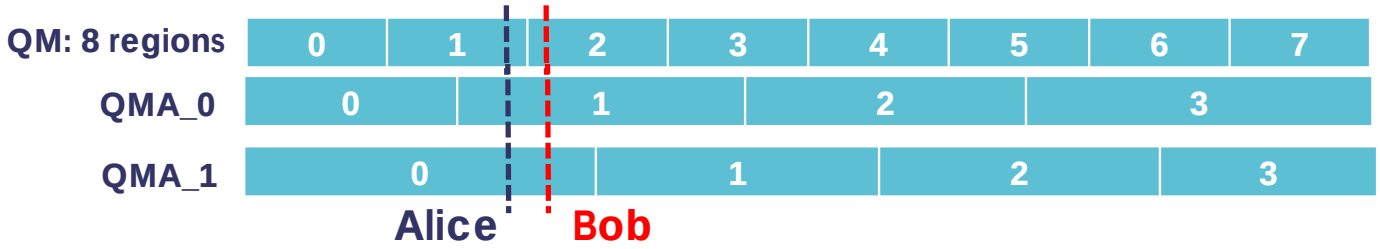


No obvious pattern is repeated in the keys

Selected Method in the following

QUANTIZATION

- Objective: generate binary symbols from channel measurements
- Possibility to quantize RSSI or Channel State Information (CSI)
- Quantization algorithm: CQA (CSI based, Wallace2010)
- Advantage of CQA: reduce mismatch between Alice and Bob keys



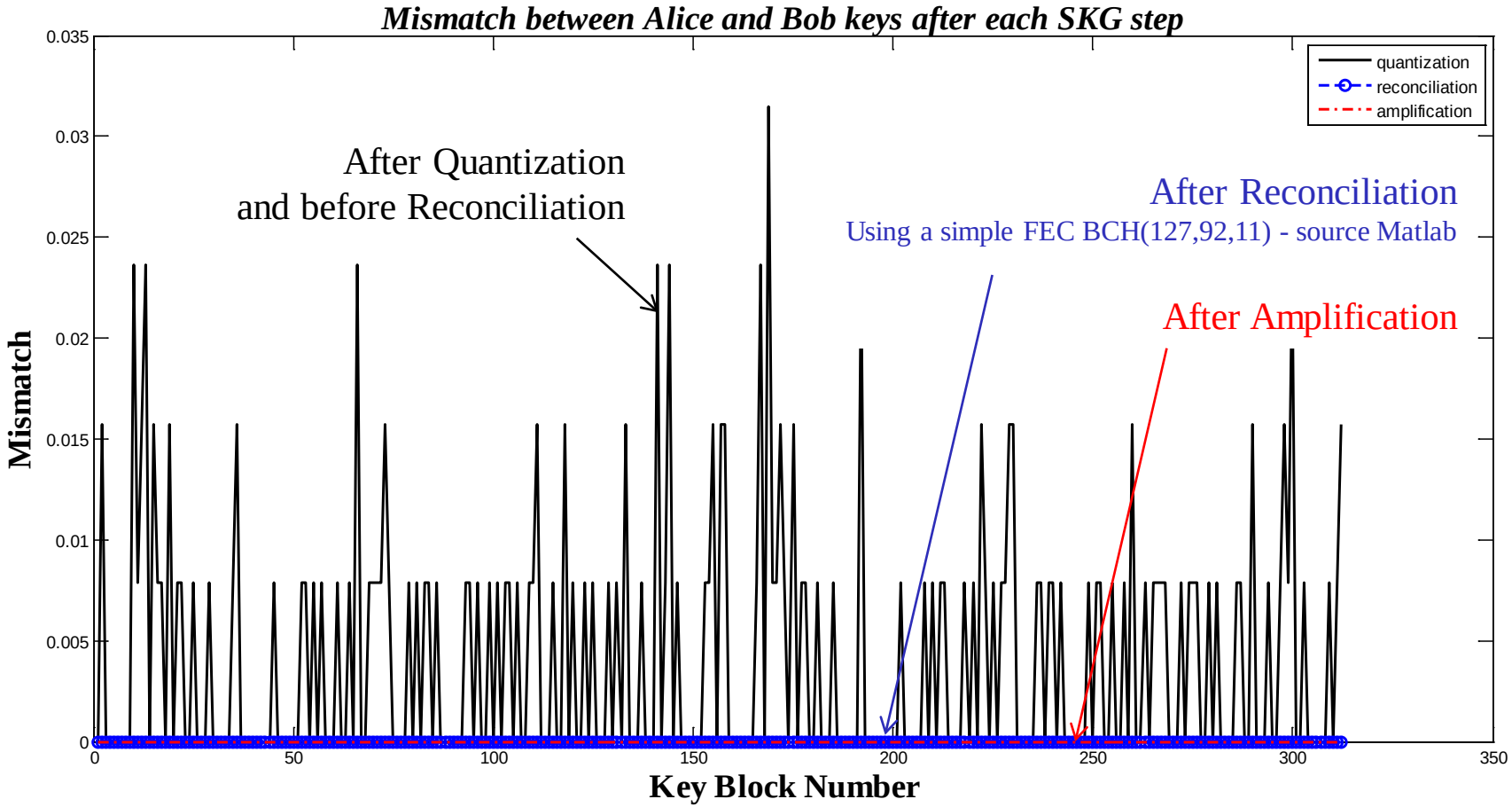
CQA ALGORITHM

- The total space of observable channel measurements is divided into regions
- Region boundaries can cause mismatch between Alice and Bob keys
- Two Maps are created and alternated to avoid this
- In CQA, Alice chooses one map (here QMA_1), evaluates the quantization symbol (0) and sends the number of the quantization map to Bob (1)
- Bob evaluate his quantization symbol using the map indicated by Alice (He also finds 0 using QMA_1)

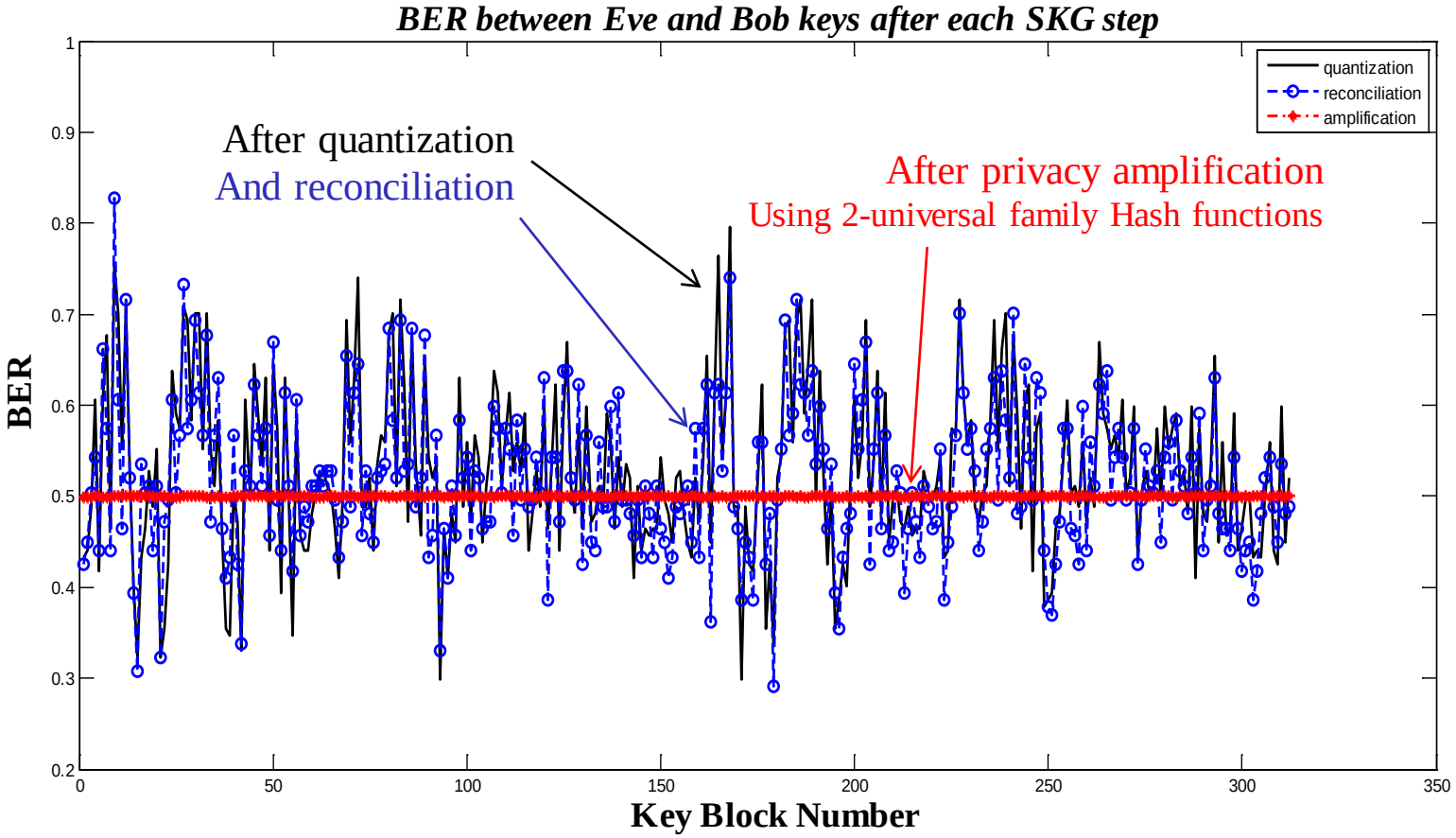
- J. W. Wallace and R. K. Sharma, "Automatic secret keys from reciprocal MIMO Wireless channels: measurement and analysis," IEEE Transactions on information forensics and security, vol. 5, no. 3, pp. 381-392, September 2010

SECOND CHALLENGE: CORRECT MISMATCH BETWEEN COMPUTED KEYS

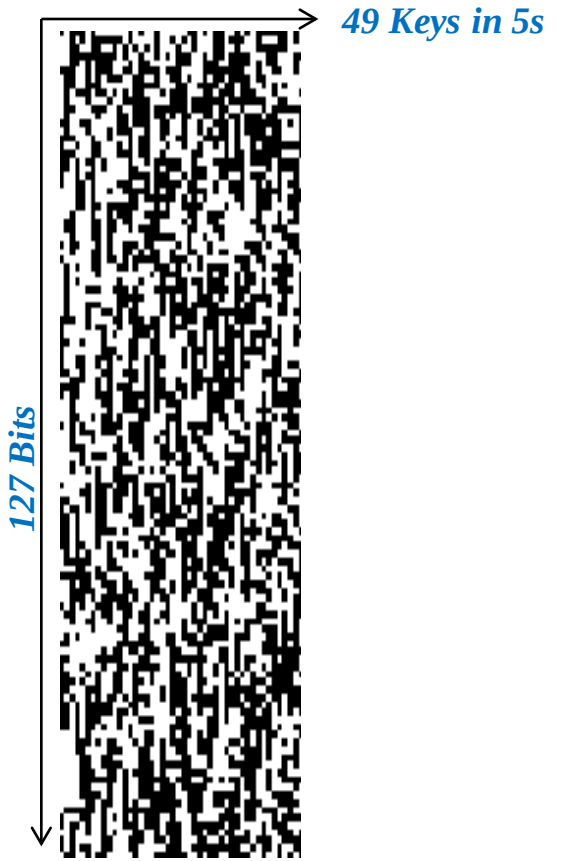
- Mismatch can occur after quantization between keys computed by Alice and Bob
- Reconciliation through FEC is necessary to achieve a perfect equality of the keys



- **THIRD CHALLENGE: ENSURING LOW INFORMATION LEAKAGE TO EVE**
  - **First criteria is a key Bit Error Rate**
    - **BER ~ 0.5 at Eve's side**
  - **Amplification deletes information on Bob's key by ensuring a BER of 0.5**
  - **Eve has no information on Bob's key**



- **FOUTH CHALLENGE: RANDOMNESS OF THE KEY IMPACT OF AMPLIFICATION STEP**
  - **LTE – Indoor (Classroom)**
  - **Keys are generated from Channel Frequency Response measured on the PSS**
    - **Frequency: 2627.5MHz**
    - **Bandwidth: 10 MHz**



- **LTE Classroom after quantization**

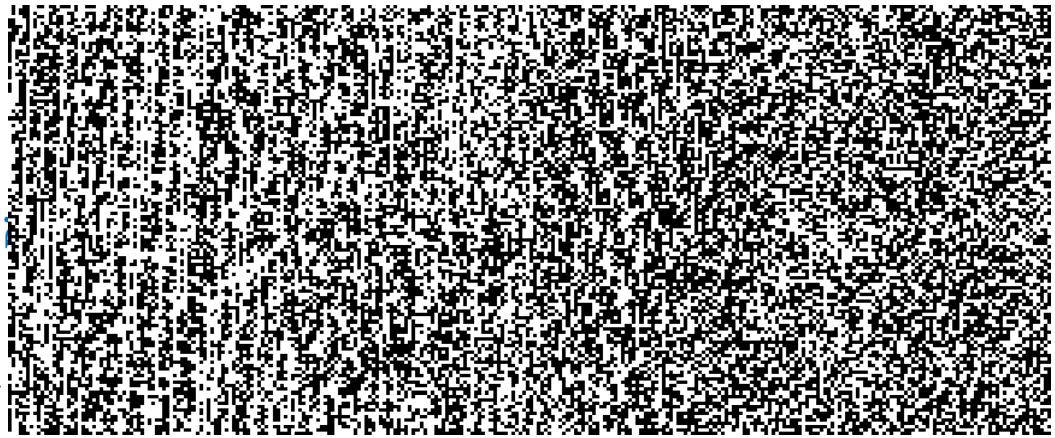
- **LTE Classroom after amplification**

- **FOUTH CHALLENGE: RANDOMNESS OF THE KEY IMPACT OF AMPLIFICATION STEP**
  - **LTE – Outdoor (street in Paris)**
  - **Keys are generated from Channel Frequency Response measured on the PSS**
    - **Frequency: 2645MHz**
    - **Bandwidth: 10 MHz**

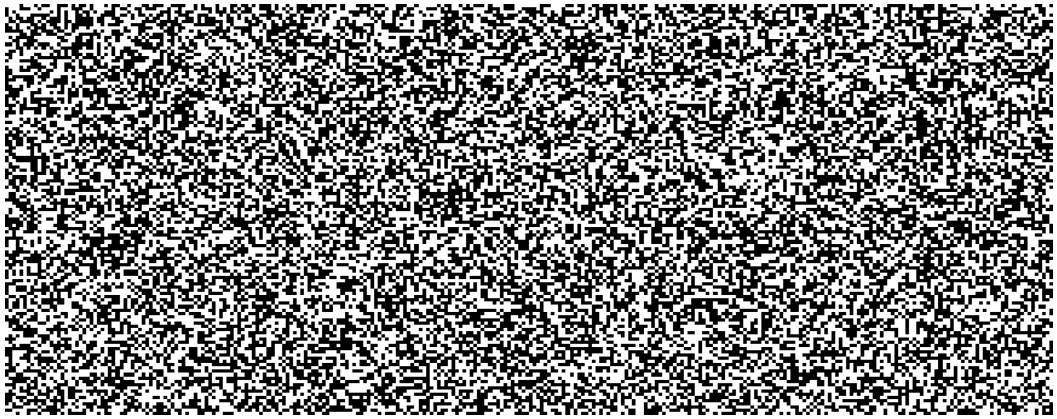
284 Keys in 5s

After quantization

127

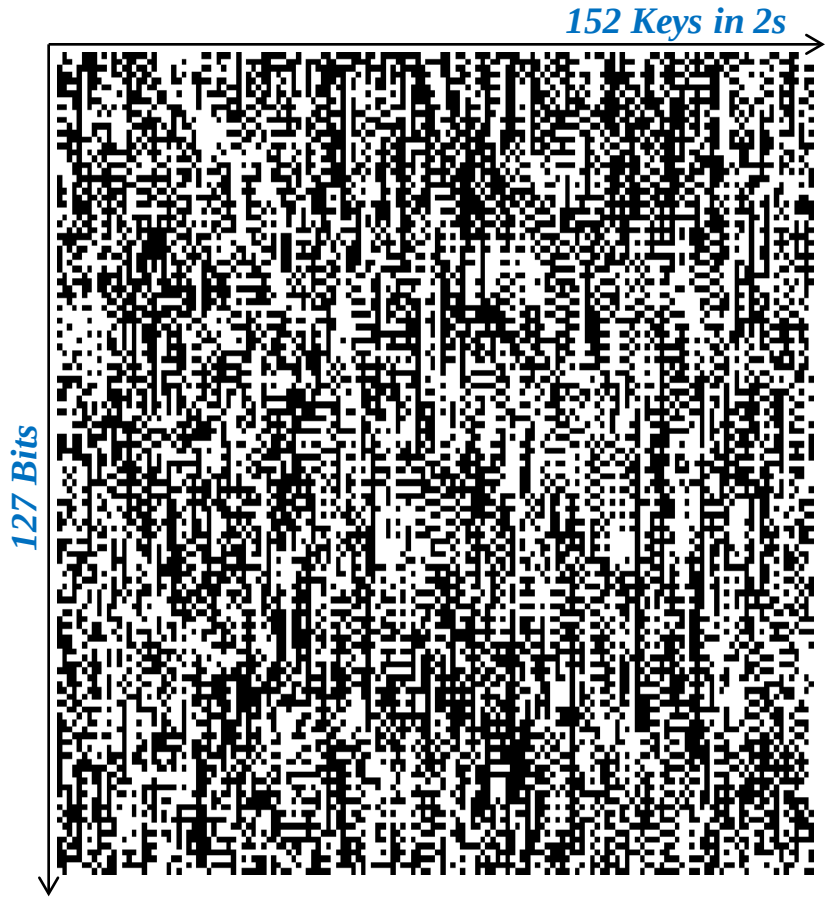


After amplification

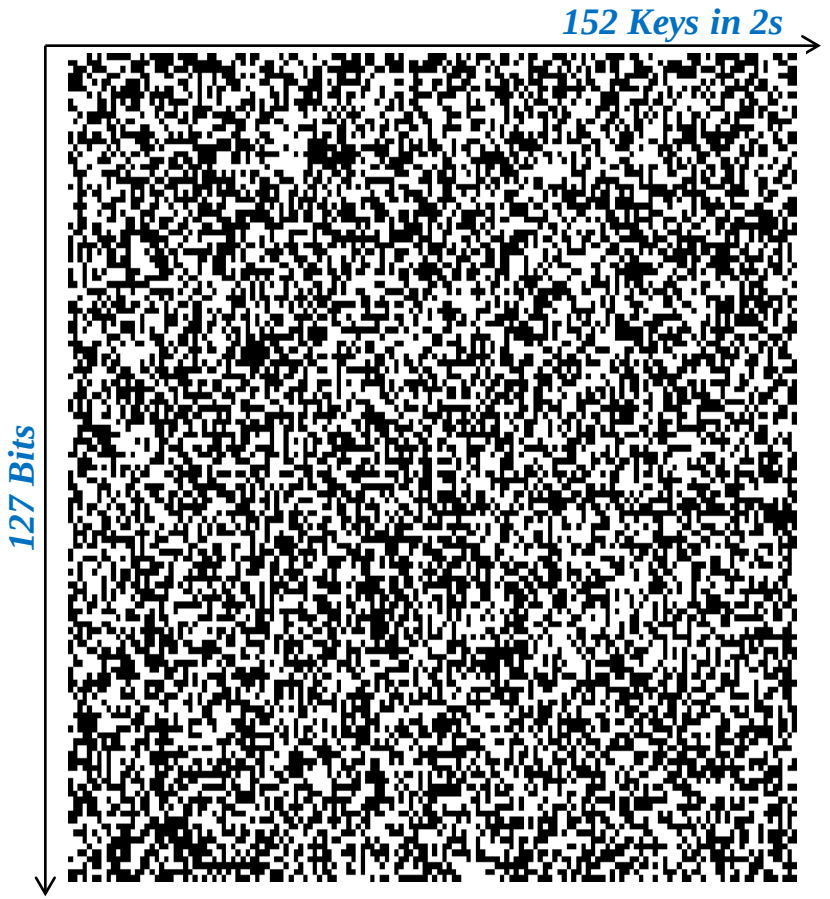


More keys are generated due to higher mobility and more scatterers in the environment

- **FOUTH CHALLENGE: RANDOMNES OF THE KEY IMPACT OF AMPLIFICATION STEP**
  - **WIFI – LOS (Indoor)**
  - **Keys are generated from Channel Frequency Response measured on the LTF**
    - **Frequency: 2462MHz**
    - **Bandwidth: 20 MHz**



- **WiFi LOS After quantization**



- **WiFi LOS After amplification**

FOUTH CHALLENGE: RANDOMNES OF THE KEY - NIST CRITERIA

- 2 NIST tests are carried out to evaluate the quality of the keys
  - **Frequency monobit test**
    - Determines whether the numbers of 0s and 1s in the key are approximately the same as would be expected for a truly random sequence.
  - **Runs test**
    - Determines whether the oscillation between 0s and 1s is too fast or too slow

- NIST frequency monobit tests

LTE	Indoor (2.6GHz)	Outdoor (2.6GHz)
Quantization	**98%** (48/49)	**99%** (281/284)
Amplification	**100%** (49/49)	**100%** (284/284)

WIFI	LOS (2.4 GHz)	NLOS (2.4 GHz)
Quantization	**87%** (132/152)	**100%** (171/171)
Amplification	**99%** (151/152)	**100%** (171/171)

- Runs tests

LTE	Indoor (2.6GHz)	Outdoor (2.6GHz)
Quantization	**27%** (13/49)	**80%** (228/284)
Amplification	**100%** (49/49)	**100%** (284/284)

WIFI	LOS (2.4 GHz)	NLOS (2.4 GHz)
Quantization	**84%** (128/152)	**99%** (169/171)
Amplification	**98%** (149/152)	**99%** (170/171)

TEMPORARY CONCLUSION ON SECRET KEY GENERATION

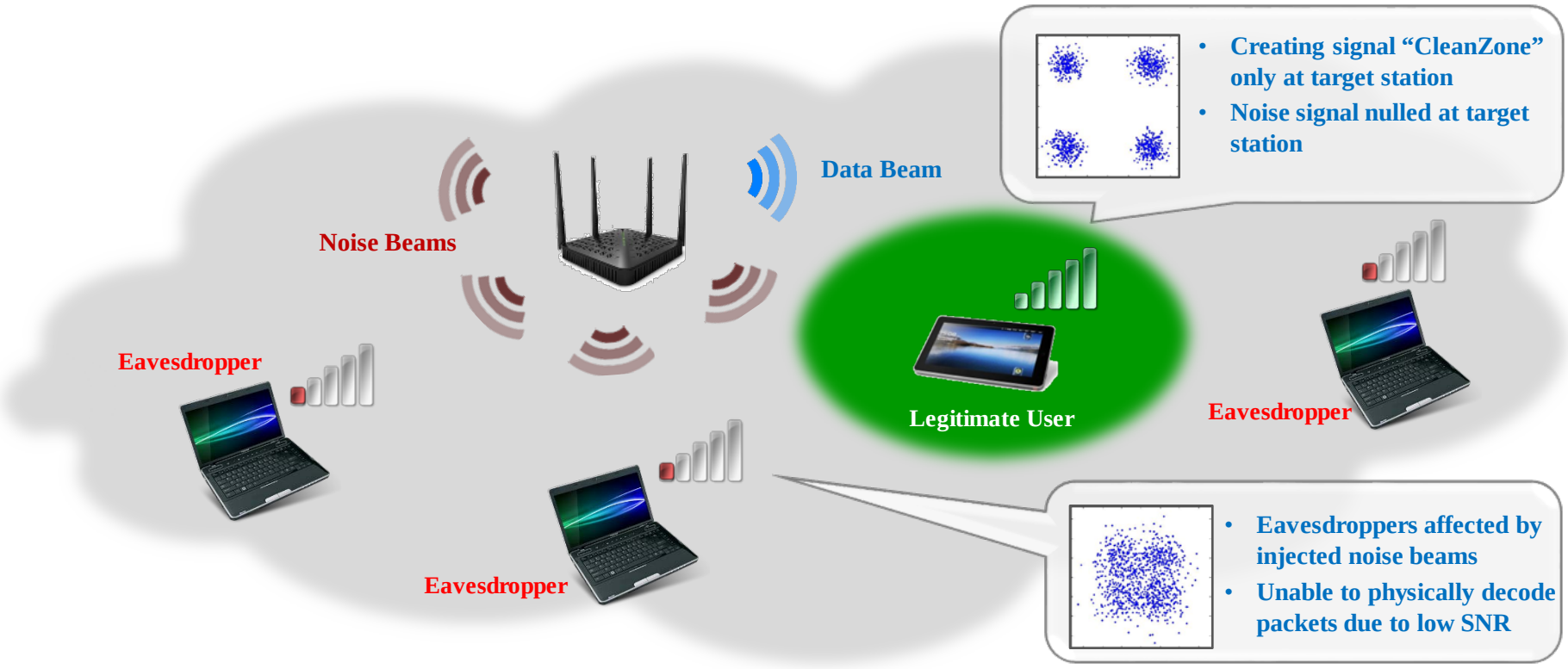
- Easy implementation
  - Low Complexity
  - Compliant with all modern digital standards
- Does not require better SNR for legitimate link than eavesdropper link
- Process provides good quality key (most often in short amount of time)
- Can take great advantage of TDD, Massive MIMO and Full-Duplex technologies
- However, provides limited results in stationary environment

EXPECTED UPGRADES IN VERY SHORT TERM

- Quality, length and rate of the key depends on the environment
  - Low diversity in some LOS environment
    - Longer time required to extract enough entropy to obtain good keys
    - Otherwise, Eve may recover the key in stationary and very low diversity case
  - New algorithms are expected to remove all the predictable components of the CFR
- For low SNR, reconciliation between Alice and Bob can be increased
  - Higher correction capacity of the codes uses by Alice and Bob for reconciliation
- Trade-off between algorithm complexity and
  - Mismatch between Alice and Bob
  - Information leakage
  - Quality of the key

PRINCIPLE ON MISO OR MIMO RATS

- PHY level security based on beamforming and directional artificial noise (AN) jamming
- Transmission of orthogonal noise beams that force very low SNR anywhere in space other than in a small sphere surrounding the legitimate user
- The result is high SNR at the legitimate user spatial location and very low SNR elsewhere
- Unlike standard encryption, e.g. WPA2, AN is "unbreakable" and is immune to offline processing attacks. Eavesdropper cannot even recover the bits by offline processing



IMPLEMENTATION OF ARTIFICIAL NOISE (AN) IN WIFI

- The 802.11ac/n frame has two parts to the preamble
  - Legacy part: used for initial synchronization
  - VHT part: used for channel estimation.
  - Beamforming mode is applied from VHT part onwards
- AN can be added from
  - The legacy part

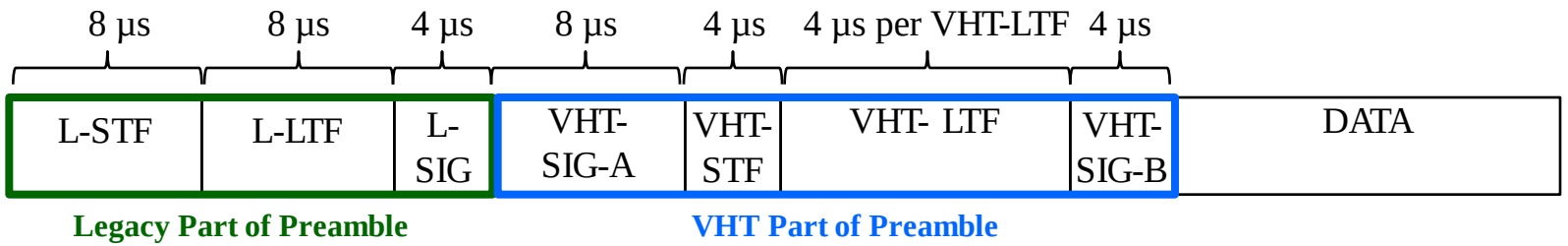
    Pro: can disrupt Eve synchronization

    Con: gives Eve more time to estimate (and supress) spatial noise
  - The VHT part of preamble

    Pro: Bob can estimate residual noise

    Con: degrades channel estimate for Bob. Still allows Eve to estimate direction of spatial noise
  - Data

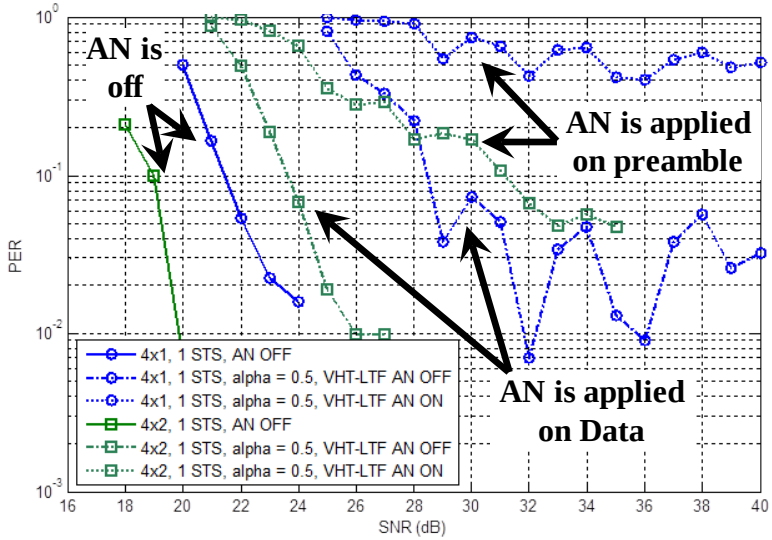
    Pros: Bob has clean channel estimate. Eve cannot estimate noise from known preamble.



SIMULATIONS PARAMETERS

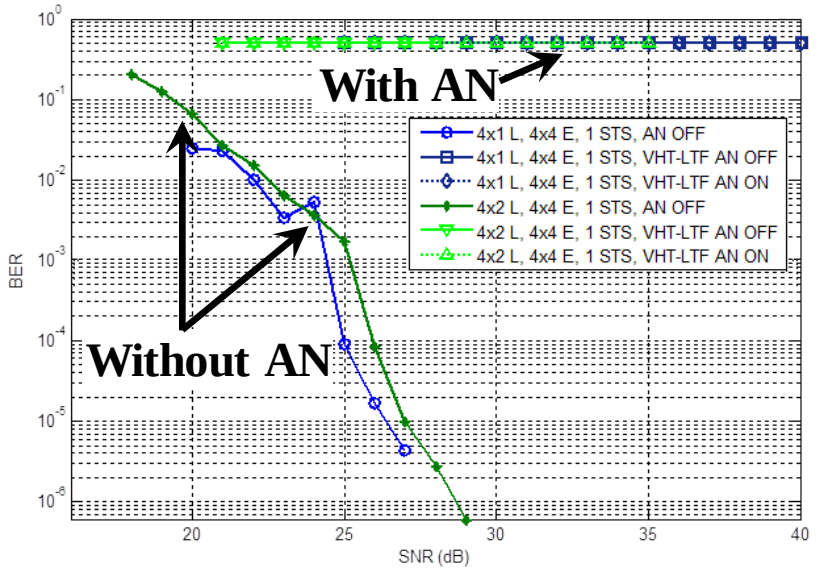
- Power allocation to noise is 50%
- Simulation includes effect of CSI quantization
- Communication scenario
  - 4xTX Alice
  - Number of spatial stream: 1
  - Constellation: 64-QAM
  - Rate: 5/6
  - 1xRX Bob (addition of 3 noise streams)/ 2xRX Bob (addition of 2 noise streams)
  - 4xRX Eve. Eve was modeled as a "standard" receiver

PER for Bob in different AN schemes



- Performance loss for single antenna Bob is 7dB when AN applied from Data portion
- Application of AN on preamble significantly increases noise

BER for different AN schemes



- BER for Eve is 50% for every cases

- **CONCLUSION ON ARTIFICIAL NOISE**
  - **Easy implementation**
    - **Low Complexity**
    - **Compliant with all modern digital standards**
    - **Take advantage of space time block coding for security purposes**
  - **Provide radio advantage for legitimate link**
    - **Even if Eve has more antennas than Bob**
    - **Independent on the Modulation Coding Scheme (MCS)**
    - **Resilience against offline processing**
  - **Provides suitable conditions for secrecy coding**

- **LIMITS**
  - **CSI must be protected from Eve**
    - **Protection can be decreased if channel matrix is revealed**
    - **Necessity to protect of sounding frame**
  - **What if Eve has more antennas capabilities ?**

- **OBJECTIVE OF SECRECY CODING**
  - Designing error correcting codes with secrecy capacity
  - Providing reliable communication to legitimate users by approaching the Shannon capacity
  - Mitigating the information for any Eavesdropper (at any other location)
- **REQUIREMENTS**
  - Legitimate link must have a better radio link (~SNR in AWGN channel) than Eve
- **MAIN CHALLENGES**
  - Existence of optimal Secrecy Codes is proven. No straightforward general design method
  - Explicit secrecy code construction only for « ideal » channel models (BEC, BSC)
  - Existing design of polar codes for the wiretap AWGN channel applies only for very long code length (2^{20})
  - Researches are in progress for advanced channel models (lattice coding, etc.)
- **PROPOSAL FOR A (SIMPLIFIED) SECRECY CODING SCHEME**
  - Take advantage of the secrecy properties of the polar code
  - Mitigate the poor finite-length performance of the polar code by exploiting the error-correction capability of LDPC codes

THE PROPOSED SECRECY CODING (SIMPLIFIED) SCHEME

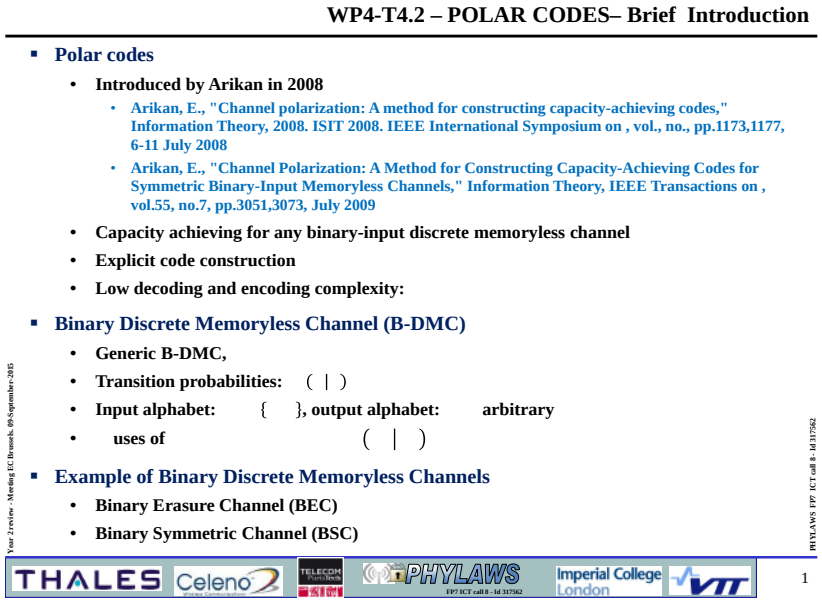
- **Concatenation of two codes**
  - **Outer code: a polar code to provide secrecy**
  - **Inner code: any error-correcting code able to provide sufficient error correction capability**

POLAR CODES

- **Construction**
  - **Length of the code: $N = 2^n$**
  - **Design of finite-length polar code is dependent on a target channel's error probability**
- **Advantages of polar codes**
  - **Capacity achieving code for binary input symmetric discrete memoryless channels**
  - **Explicit code design**
  - **Low encoding and decoding complexity: $O(Nlog(N))$**
  - **Provide secrecy over the AWGN channel when the block length goes to infinity**
- **Drawbacks**
  - **Poor decoding performance at moderate and short block length**
  - **Not pratical for real communication systems**

- **DESIGN OF THE LDPC CODE (AS SIMPLE AND CLASSICAL AS POSSIBLE)**
  - **Quasi-Cyclic LDPC code defined in the 802.11 standard**
  - **Length of the code: $N = 1296$**
  - **Rate of the code: $R = 5/6$**

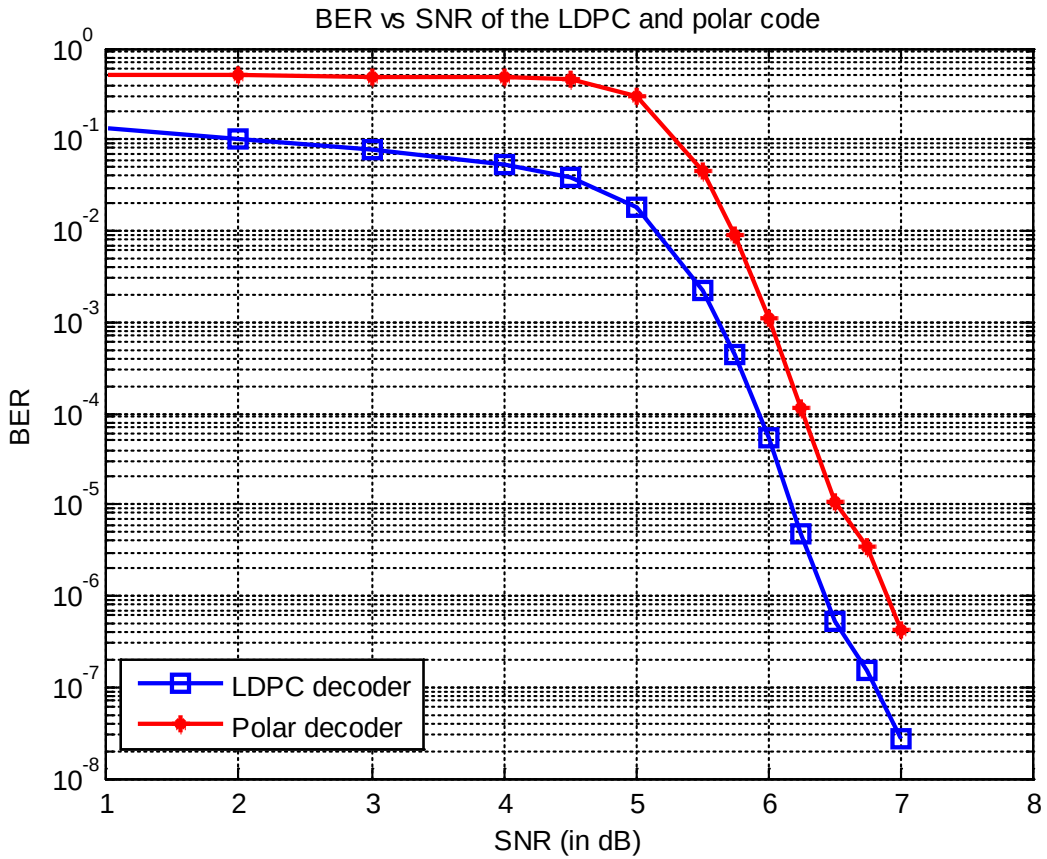
- **DESIGN OF POLAR CODE**
  - **From Information Theory**
    - H.Mahdavifar and A.Vardy, "Achieving the secrecy capacity of wiretap channels using polar codes,", 57 ed IEEE Transactions on Information Theory, 2011, pp. 6428-6443



WP4-T4.2 – POLAR CODES– Brief Introduction

- Polar codes
  - Introduced by Arikan in 2008
    - Arikan, E., "Channel polarization: A method for constructing capacity-achieving codes," Information Theory, 2008. ISIT 2008. IEEE International Symposium on , vol., no., pp.1173,1177, 6-11 July 2008
    - Arikan, E., "Channel Polarization: A Method for Constructing Capacity-Achieving Codes for Symmetric Binary-Input Memoryless Channels," Information Theory, IEEE Transactions on , vol.55, no.7, pp.3051,3073, July 2009
  - Capacity achieving for any binary-input discrete memoryless channel
  - Explicit code construction
  - Low decoding and encoding complexity:
- Binary Discrete Memoryless Channel (B-DMC)
  - Generic B-DMC,
  - Transition probabilities: (|)
  - Input alphabet: { }, output alphabet: arbitrary
  - uses of (|)
- Example of Binary Discrete Memoryless Channels
  - Binary Erasure Channel (BEC)
  - Binary Symmetric Channel (BSC)

- **FIRST SIMULATIONS WITH GENERATED QPSK SIGNALS**
- **CODE PARAMETERS**
  - $N = 2^{10} = 1024$
  - AWGN
  - QPSK Modulation
  - Belief propagation algorithm to decode LDPC and polar codes
  - Final secrecy code rate: 0.35



- **RESULTS AT THE OUTPUT OF THE SECRECY CODING SCHEME**

  BER = 0.5 when SNR ≤ 4 dB

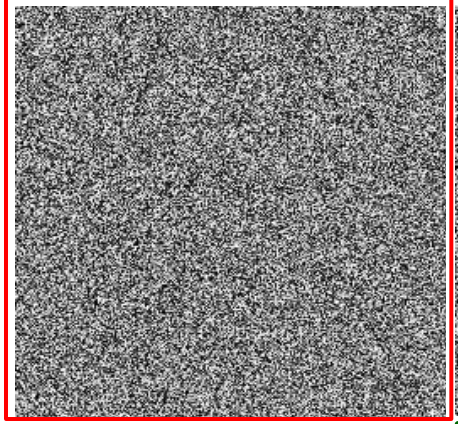
  BER < 10-5 when SNR ≥ 6.5 dB

  Security gap (~ Min radio advantage): 2.5 dB

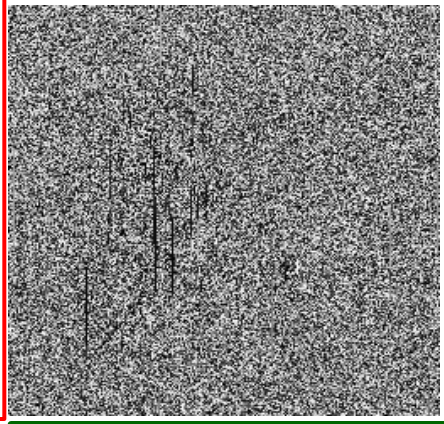
Original Image (to be sent over the wiretap channel)

IMAGE RECEIVED BY EVE

Received image, SNR = 4dB



Received image, SNR = 4.5dB

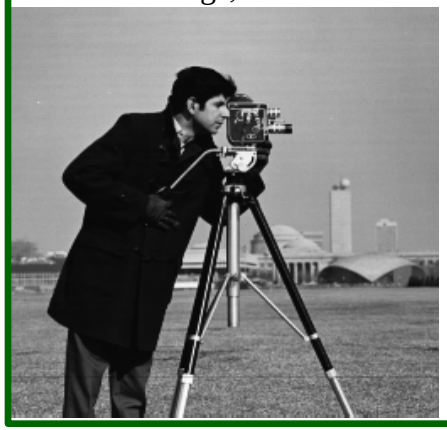


Received image, SNR = 5dB

Received image, SNR = 5.5dB

Received image, SNR = 6dB

Received image, SNR = 6.5dB



Received image, SNR = 7dB

IMAGE RECEIVED BY BOB

- **PERFORMANCE ILLUSTRATION (TRANSMISSION AN IMAGE)**
  - **The received image contains random pixels when SNR ≤ 4 dB**
  - **Perfect reception of the image when SNR ≥ 6.5 dB**

Security gap : 2.5 *dB*
~ Min radio advantage

SUMMARY OF WORK ON SECRECY CODING

- Evidence that Eve's BER should be close to 0.5
  - At SNR = 5 dB, BER = 0,297 but Eve can guess the transmitted image from the received one
- The polar code provides security
  - Thanks to the polar code BER = 0.5 when SNR ≤ 4dB
  - No information is leaked to Eve
- Poor overall performance of the polar code (due to the small length of the code)
  - Final BER is always higher than the error probability of the BSC channel (LDPC decoder BER)
- The LDPC code provides reliability
  - Good transition to the waterfall region, no error floor at 10^{-8}

PROVISORY CONCLUSION ON SECRECY CODING

- Do not require mobility or scatterers in the environment
- Secrecy code requires better SNR for legitimate link than eavesdropper link
- Reliability is ensured by LDPC codes
  - already widely used in wireless standard
- Secrecy is achieved by only adding a polar code
  - Low encoding and decoding complexity
  - Loss of reliability (0.5 to 1 dB) due to short length of polar code using belief propagation

Thank you for your attention

Find more information on our website

www.phylaws-ict.org

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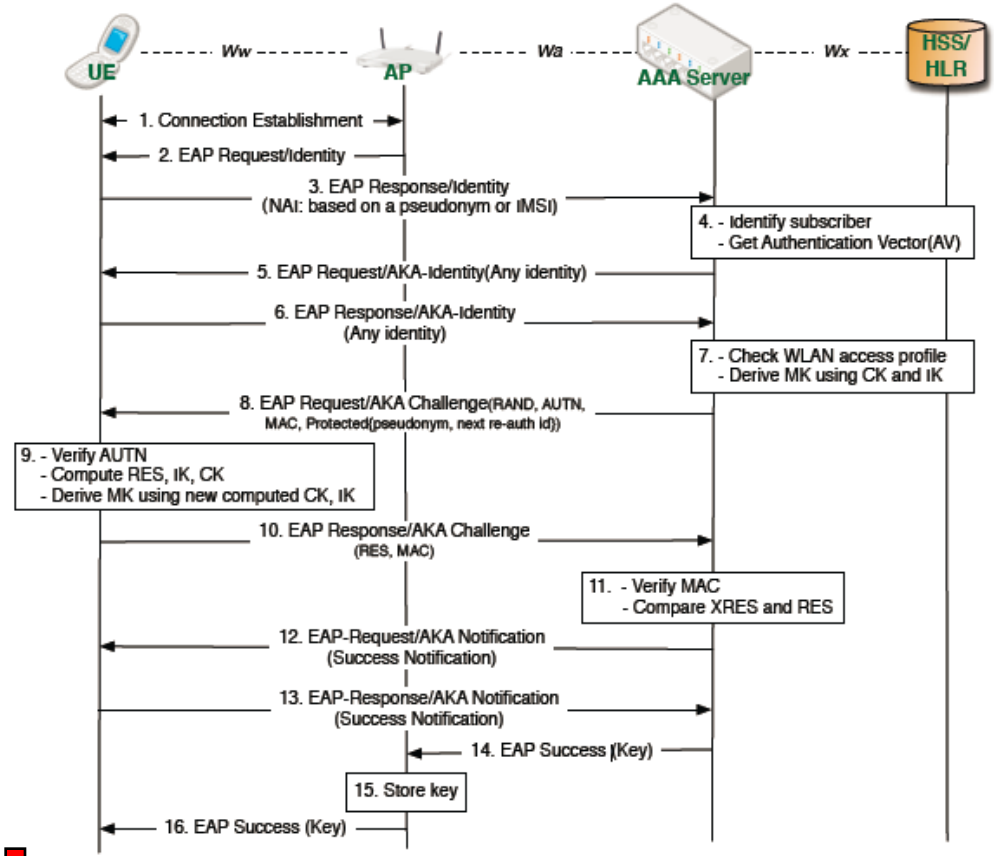
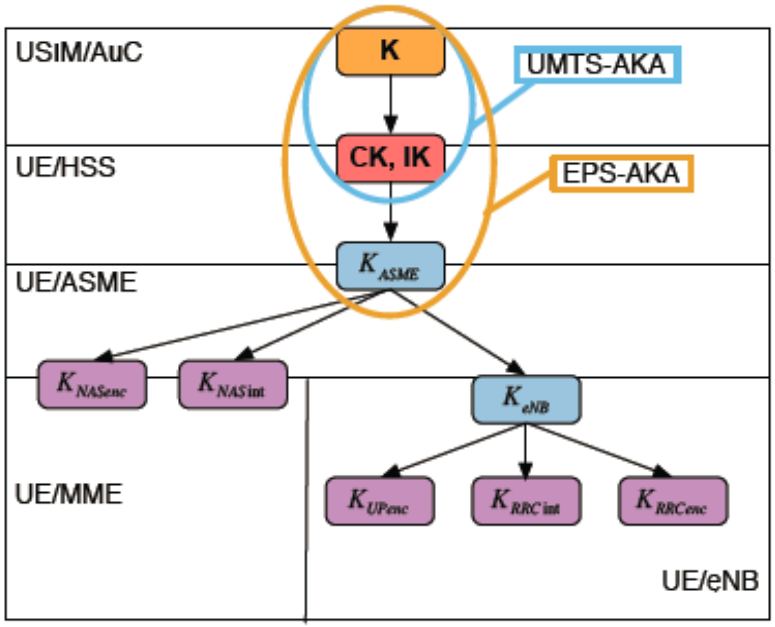
GLOSSARY

AN	Artificial Noise
BCH	Bose Ray-Chaudhuri Hocquenghem
BER	Bit Error Rate
BTS	Base Transceiver Station
CIR	Channel Impulse Response
CFR	Channel Frequency Response
CQA	Channel Quantization Algorithm
COMSEC	Communication Security
CRS	Cell-specific Reference Signal
FDD	Frequency Division Duplex
FEC	Forward Error Correction
GSM	Global System for Mobile communications
IMSI	International Mobile Subscriber Identity
LDPC	Low Density Parity Check
LOS	Line Of Sight
LTE	Long Term Evolution
LTF	Long Training Field
MAC	Media Access Control
MIMO	Multiple Input Multiple Output
NIST	National Instrument of Standards and Technology
NETSEC	Network Transmission Security
NLOS	Non Line Of Sight
PHYSEC	Physical Layer Security
PSS	Primary Synchronization Sequence
RAT	Radio Access Technology
SIM	Subscriber Identity Module
SKG	Secret Key Generation
SNR	Signal to Noise Ratio
SS7	Signaling System No.7
SSS	Secondary Synchronization Sequence
TDD	Time Division Duplex
TMSI	Temporary Mobile Subscriber Identity
TRANSEC	Transmission Security
UMTS	Universal Mobile Telecommunications System
VIP	Very Important People

APPENDIX 1– INTEREST OF PHYSEC: More on security lacks in mobile network

Hyeran Mun, Kyusuk Han and Kwangjo Kim1-4244-2589-1/09/ $20.00 2009 IEEE,
"3G-WLAN Interworking: Security Analysis and New Authentication and Key Agreement based on EAP-AKA »





K_{NASenc} : Protection of NAS traffic with particular encryption
K_{NASint} : Protection of NAS traffic with particular integrity
K_{UPenc} : Protection of UP traffic with particular encryption
K_{RRCint} : Protection of RRC traffic with particular integrity
K_{RRCenc} : Protection of RRC traffic with particular encryption

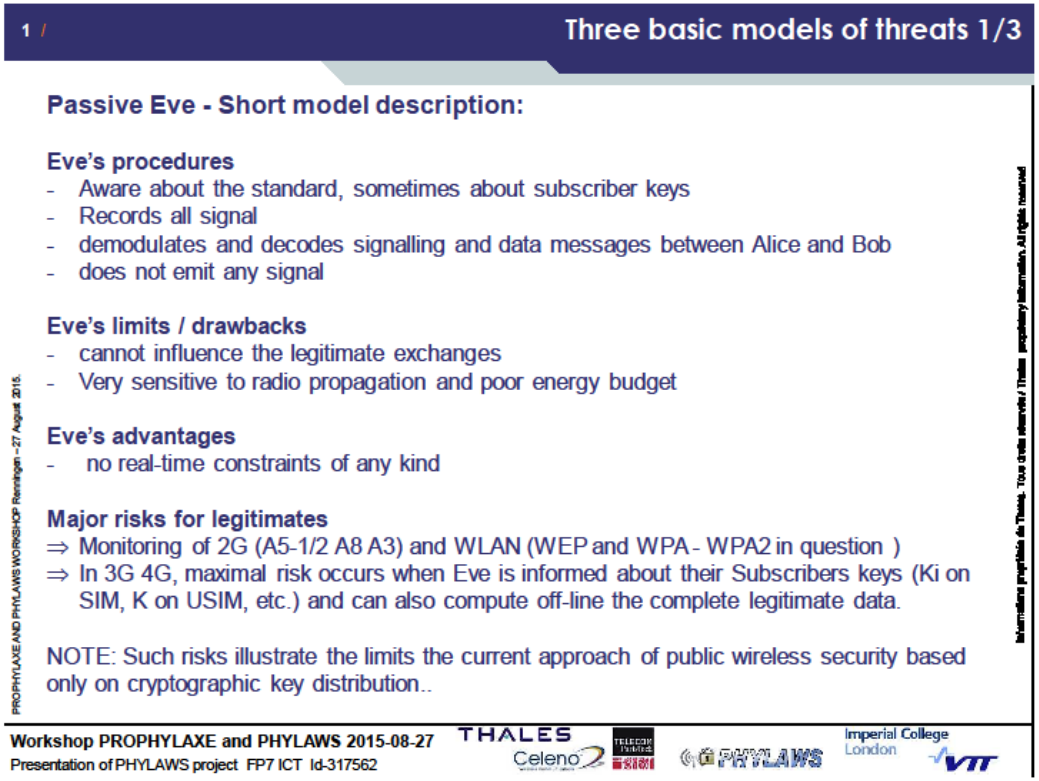
(T/I)MSI AV RAND RES etc. ARE EXCHANGED IN CLEAR TEXT WITHOUT TRANSEC PROTECTION
→ PASSIVE EVE CAN DECODE
→ ACTIVE EVE CAN JAM, SPOOF, REPLAY…

WHEN EVE GET THE KEY K SHE GETS ALL…
…BY PASSIVE MONITORING ONLY.

Basics of PHYsical LAyer Wireless Security

FWD sense - Wiretap channel – Passive Eve

THREE BASIC MODELS OF THREATS



1 / Three basic models of threats 1/3

Passive Eve - Short model description:

Eve's procedures
- Aware about the standard, sometimes about subscriber keys
- Records all signal
- demodulates and decodes signalling and data messages between Alice and Bob
- does not emit any signal

Eve's limits / drawbacks
- cannot influence the legitimate exchanges
- Very sensitive to radio propagation and poor energy budget

Eve's advantages
- no real-time constraints of any kind

Major risks for legitimates
⇒ Monitoring of 2G (A5-1/2 A8 A3) and WLAN (WEP and WPA - WPA2 in question)
⇒ In 3G 4G, maximal risk occurs when Eve is informed about their Subscribers keys (Ki on SIM, K on USIM, etc.) and can also compute off-line the complete legitimate data.

NOTE: Such risks illustrate the limits the current approach of public wireless security based only on cryptographic key distribution..

PROPHYLAXE AND PHYLAWS WORKSHOP Renningen – 27 August 2015.

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Workshop PROPHYLAXE and PHYLAWS 2015-08-27
Presentation of PHYLAWS project FP7 ICT Id-317562

- **OBJECTIVE**
  - **Eliminate any mismatch after quantization between Alice and Bob keys**
  - **Minimize information leakage to Eve**
- **SECURE SKETCH BASED ON ERROR-CORRECTING CODES**
  - **Outputs public information *s* about an input *K***
  - **Does not reveal *K* but allows exact recovery of *K* given *K'* close to *K***
- **INFORMATION RECONCILIATION ALGORITHM STEPS**
  - **Alice:**
    - **selects a random codeword c from an error-correcting code $\mathcal{C}$**
    - **computes the secure sketch $s = K_a \oplus c$**
    - **sends the shift s to Bob over the public channel**
  - **Bob:**
    - **Bob subtracts s from its key K_b : $c_b = K_b \oplus s$**
    - **Bob decodes c_b to recover the random codeword c_b and gets $\hat{c}$**
    - **Bob computes K_a by shifting back and gets: $\widehat{K_a} = \hat{c} \oplus s$**

Y. Dodis, R. Ostrovsky, L. Reyzin, and A. Smith, "Fuzzy extractors: How to generate strong keys from biometrics and other noisy data," SIAM J. Comput., vol. 38, no. 1, pp. 97–139, 2008.

Qian Wang; Hai Su; Kui Ren; Kwangjo Kim, "Fast and scalable secret key generation exploiting channel phase randomness in wireless networks," INFOCOM, 2011 Proceedings IEEE , vol., no., pp.1422,1430, 10-15 April 2011

- **OBJECTIVE**
  - **Reduce Eve's amount of information on the key**
  - **Improve the randomness of the key**
  - **Can be performed using hash function or extractors**
    - **We choose a two-universal family of hash functions**

- **TWO-UNIVERSAL FAMILY OF HASH FUNCTIONS**
  - **A class $\mathcal{G}$ of functions $\mathcal{A} \rightarrow \mathcal{B}$ is two-universal if for all $x_1 \neq x_2$:**

$$\Pr[g(x_1) = g(x_2)] \leq \frac{1}{|\mathcal{B}|}$$

when g is chosen randomly from $\mathcal{G}$

- **CONSTRUCTION OF A TWO-UNIVERSAL FAMILY OF HASH FUNCTIONS**
  - **Select a random element $a \in GF(2^n)$ and interpret the key K as an element of $GF(2^n)$**
  - **Consider the function $\{0,1\}^n \rightarrow \{0,1\}^r$ assigning to K the first r bits of $aK \in GF(2^n)$**
  - **2-Universal family of hash functions for $1 \leq r \leq n$**

Bennett, C.H.; Brassard, G.; Crepeau, C.; Maurer, U.M., "Generalized privacy amplification," Information Theory, IEEE Transactions on , vol.41, no.6, pp.1915,1923, Nov 1995