Combined Network Coding and Paillier Homomorphic Encryption for ensuring Consumer Data Privacy in Smart Grid Networks

Presented by David Murray, PhD candidate on behalf of the team:

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Monitoring domestic energy usage within the smart grid

- How will smart meters be used?
  - Automatic and accurate billing, improve energy usage
  - Enhance energy distribution and efficiency
- How can signal information processing/data analytics turn smart meter data into ‘useful’ information?
  - Inform and enhance current energy information
  - Provide itemised billing down to individual appliances and activities
  - Provide advice on retrofit advice
- How much and what kind of data do we need for effective data analytics?
  - Electricity, temperature, light, humidity, occupancy
  - Data collection 15mins, 1min, 30 sec, 1sec…
- Can we draw better conclusions from individual/household detailed energy consumption?

➢ How is data collected, where does it go?

➢ How do we ensure privacy of data and detect tampering?

How we implemented it at Strathclyde to gather smart meter readings

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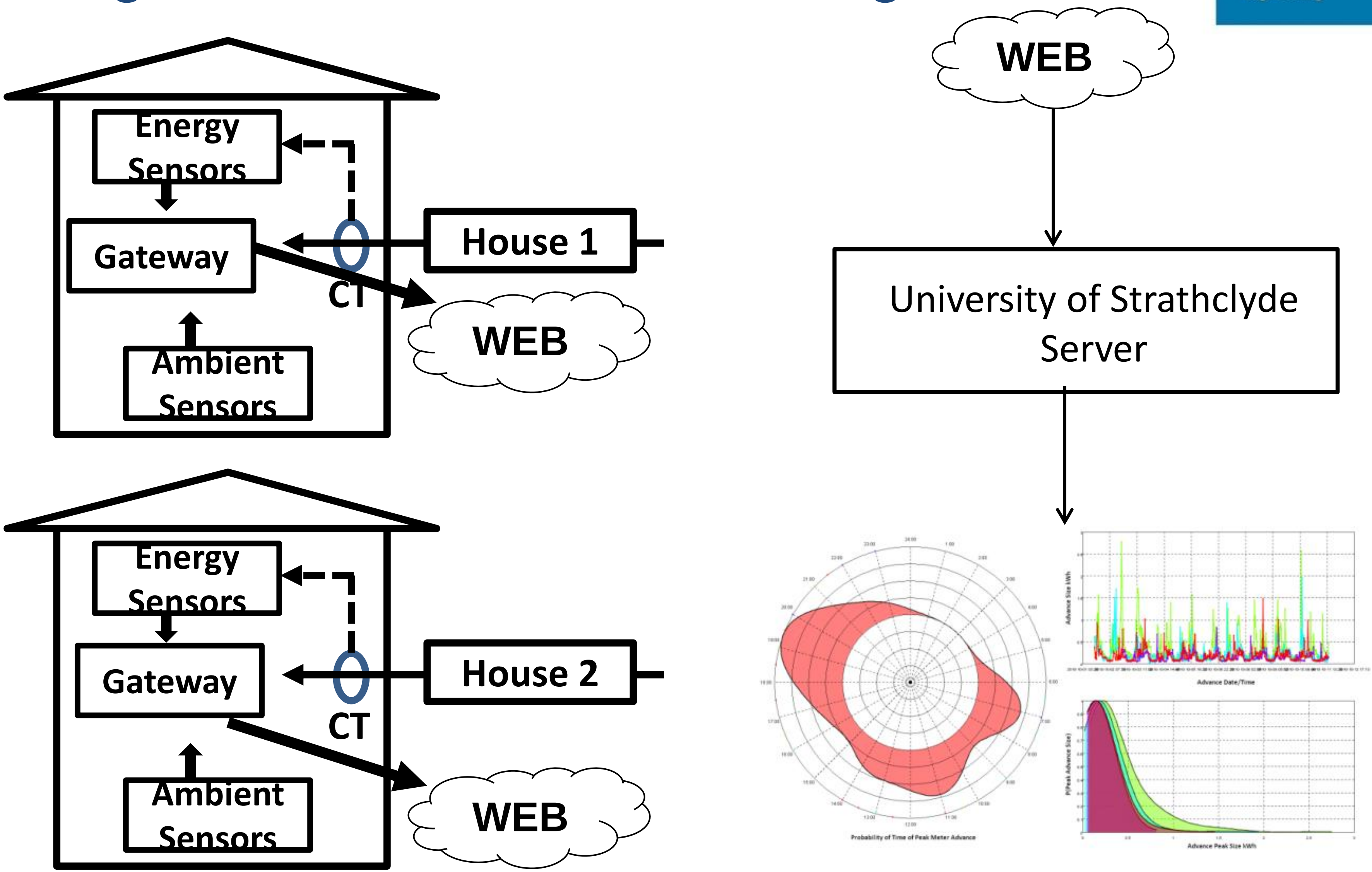
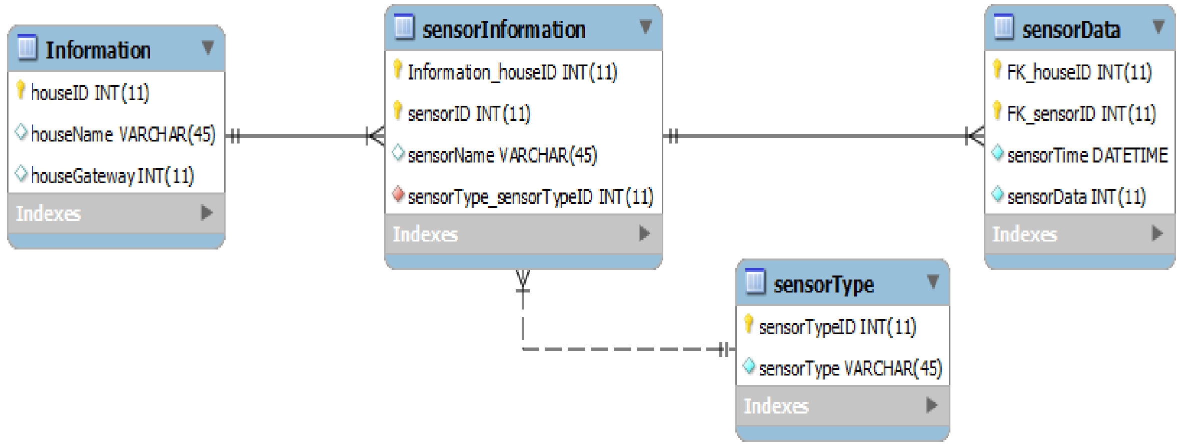
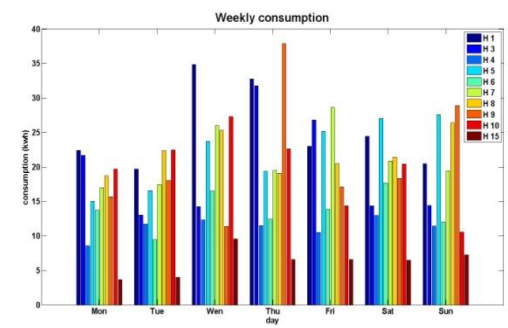


From data acquisition to analytics





Energy, Environmental & Occupancy Sensors → Real-Time Display → Gateway → Server Database → Data Checking & Cleaning → Statistical & Predictive Analysis

Analytics to provide intuitive feedback

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- We developed a scalable database that effectively manages incoming smart meter data, and provides an easy-to-query design

- Designing and developing robust and low-complexity non-intrusive load monitoring disaggregation algorithms for low sampling rate load data (< 1 Hz)

- Appliance characterisation and modelling to provide appliance upgrade recommendations

Data acquisition, management and repository

- An automated platform for remote data collection and real-time monitoring
  - Including remote and non-broadband customers
  - Keeping communications between home and server to a bare minimum, without compromising on data quality

- Scalable repository of energy and environmental measurements
  - Data checking
  - Easy to add/remove sensors and houses
  - Query for correlations amongst sensor readings in the database
  - Query for correlations across houses (e.g., compare refrigerator consumption across selected houses)
  - Collecting/processing data in real time from a large number of houses (currently 40 houses)

Power Disaggregation

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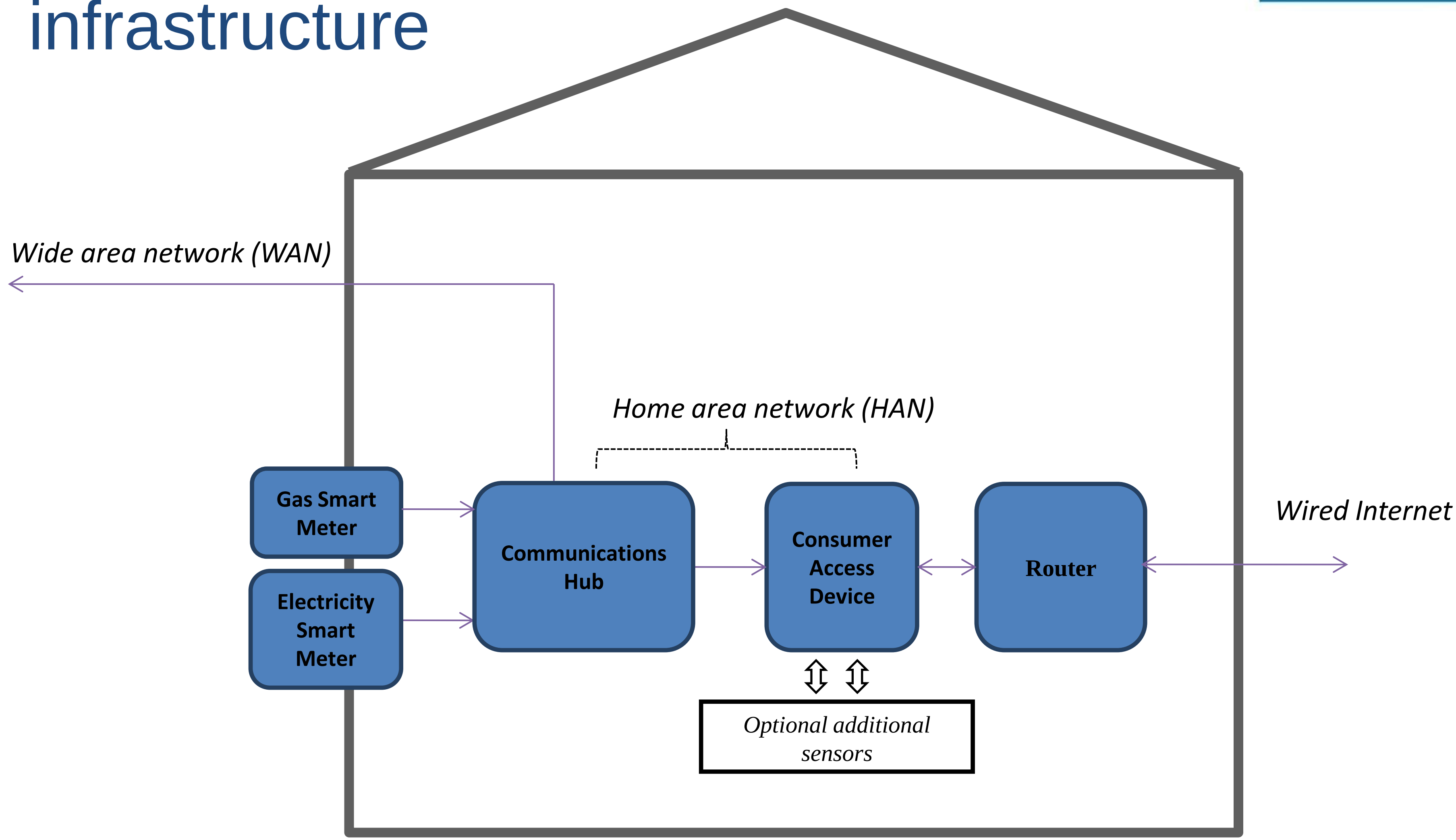
- Non-intrusive appliance load monitoring (NALM): Algorithmic solutions to disaggregate overall household's power readings to individual appliances

- Find the consumption of individual appliances without using separate individual appliances power meters (IAMs)

- Activity modelling allows for more relative feedback that people can understand and adjust habits
  - Improve: You used X amount of power yesterday on the kettle
  - If you didn't over fill the kettle you could save.

- Very active research topic
  - Currently, only few commercial solutions that operate well, work only at extremely high sampling rates ~kHz

Smart Meter readings – UK Dept of Energy and Climate Change infrastructure



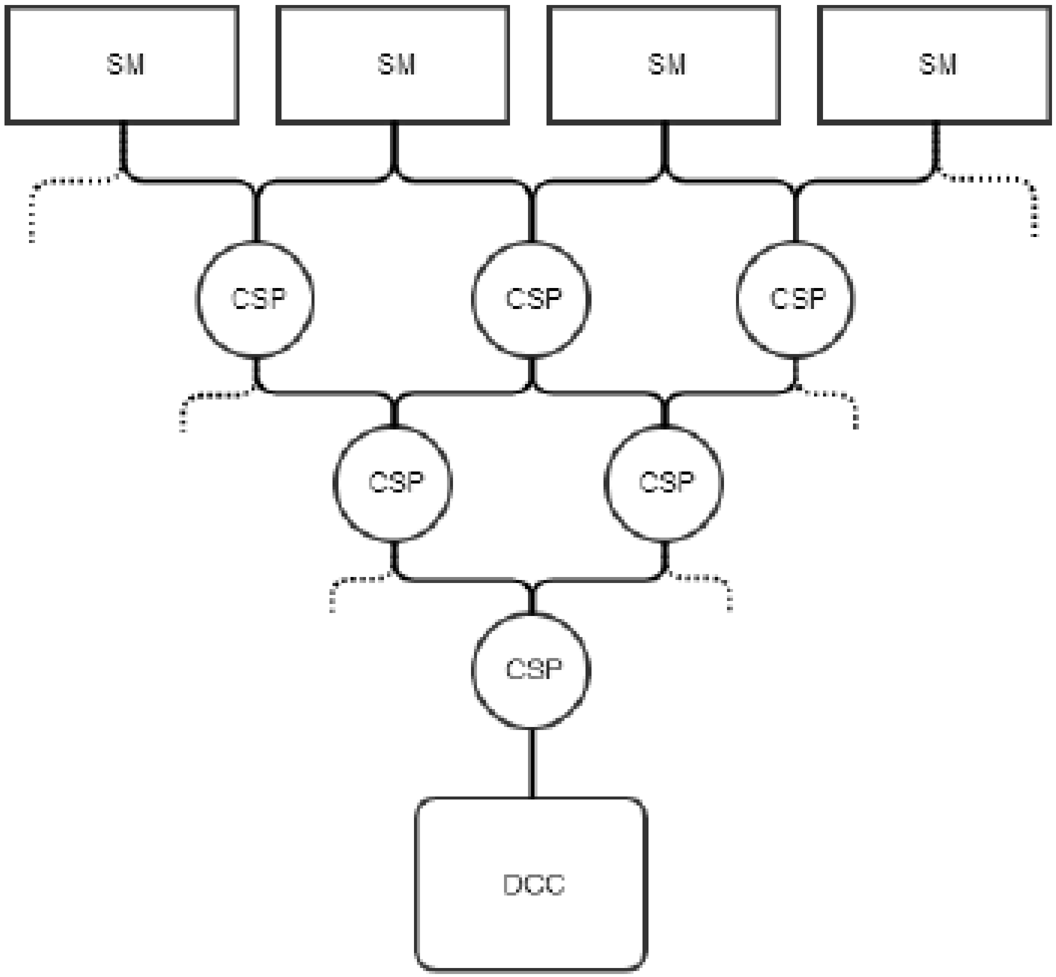
Block diagram from REFIT project team

Smart grid communications architecture

- Smart metering (SM) system located in houses comprises of a hug and sensor network
  - HAN based on 2.4GHz and 433MHz
- From the houses, data transmitted to Communications Service Provider (CSP) via wireless NAN
  - Communication range 0.25miles
  - At least two CSPs in the range of each house
  - CSPs – routers that forward packets possibly multi-hops
- Data Communication Company (DCC) receives packets from CSP and performs processing

Dept Energy and Climate Change Doc. Ref: 13d/006, DECC UK, Dec. 2013.

Smart grid communications architecture



Problem statement

- Lots of sensitive personal household data being gathered within the HAN and transmitted via WAN/NAN

- Data contains billing information and energy consumption from which domestic routines can be inferred, inc. when the household is away on holiday…

Security in the smart grid

- Smart grid prone to cyber attacks and tampering due to sensitivity of information in the network

- Key concern is against tampering, eavesdropping and traffic analysis

- Types of attacks expected:
  - Entropy Attacks
  - Packet Erasures
  - Packet Modification / Corruption
  - Eavesdropping / Analysis

Proposed Solution

- Pairing network coding (NC) with Paillier homomorphic encryption (PHE)

- Due to its homomorphic additive and multiplicative properties, PHE simplifies computation of cipher texts and incorporation of linear NC

- *Intermediate nodes can still perform NC in the conventional manner without needing access to the systems private key*

Random Linear Network Coding (RLNC)

$$X = G * M$$

$$x_k = \sum_{i=1}^{S} g_{ik} m_i$$

$$G = \begin{bmatrix} g_{11} & g_{12} & \cdots & \cdots & g_{1S} \\ g_{21} & g_{22} & \cdots & \cdots & g_{2S} \\ \cdots & \cdots & \cdots & \cdots & \cdots \\ \cdots & \cdots & \cdots & \cdots & \cdots \\ g_{N1} & g_{N2} & \cdots & \cdots & g_{NS} \end{bmatrix} \qquad M = \begin{bmatrix} m_1 \\ m_2 \\ \cdots \\ m_S \end{bmatrix}$$

- *k*-th NC symbol/packet
- m_i – *i-th source message*
- g_{ik} *random local encoded coefficient*

Benefits compared against traditional routing

- Throughput
- Efficiency
- Scalability
- Resilience to attacks and eavesdropping

Issues

- Larger transmission overhead
- Linear dependency of coefficient vectors

Paillier Homomorphic Encryption (PHE)

p, q are two k−bit primes where k is the security parameter, are random and independent such that:
$\gcd\big(pq, (p-1)(q-1)\big) = 1$

$n = pq$
$\lambda = \mathrm{lcm}\big((p-1)(q-1)\big)$

Choose random integer g where:
$g \in \mathbb{Z}^*_{n^2}$

Check modular multiplicative inverse:
$\mu = \left(L\left(g^{\lambda}\, mod\; n^2\right)\right)^{-1} \bmod n$ where $L(\mu) = \dfrac{\mu - 1}{n}$

Public Key : (n, g)
Private Key : (λ, μ)

PHE: Encryption and Decryption

Encryption:
For a message $m \in \mathbb{Z}_n$
Select random $r \in \mathbb{Z}_n^*$
Calculate ciphertext using public key: $E(m) = c = g^m r^n \bmod n^2$

Decryption:
Given received ciphertext $c < n^2$, recover the message using private key:

$$m = D(c) = L(c^{\lambda} \bmod n^2)\mu \bmod n^2$$

Homomorphic Properties

$$E(m) = (g^m r^n) \bmod n^2$$

$$E(m_1)E(m_2) = g^{m_1+m_2}(r_1 r_2)^n (\bmod n^2) = E(m_1 + m_2)$$

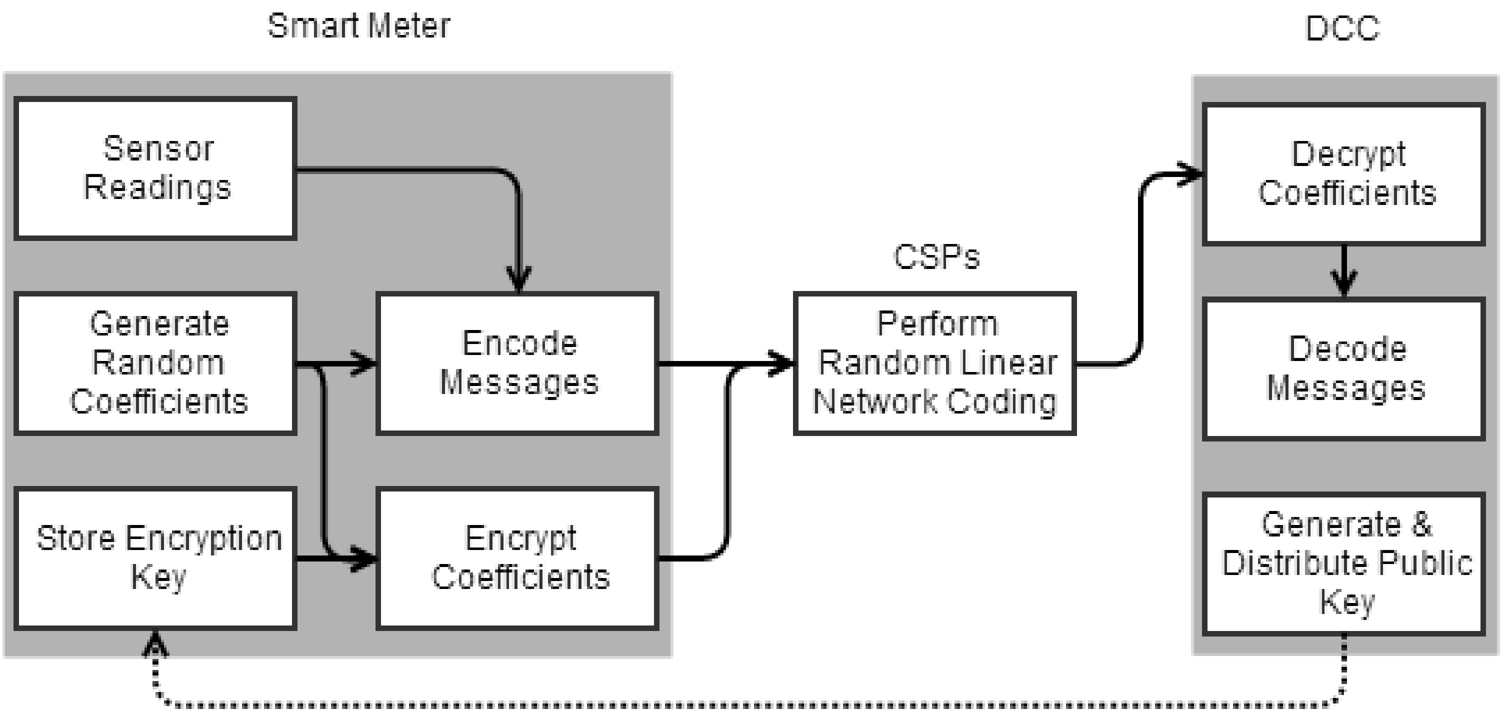
$$D(E(m_1)^k \bmod n^2) = k m_1 \bmod n$$

Threat model

We consider the threat posed by an attacker with the following characteristics:

- The attacker can eavesdrop all network links
- Has knowledge of scheme used
- Is computationally bounded
- Can inject or erase packets in the network

Proposed scheme



Proposed scheme – Combined RLNC and PHE encryption

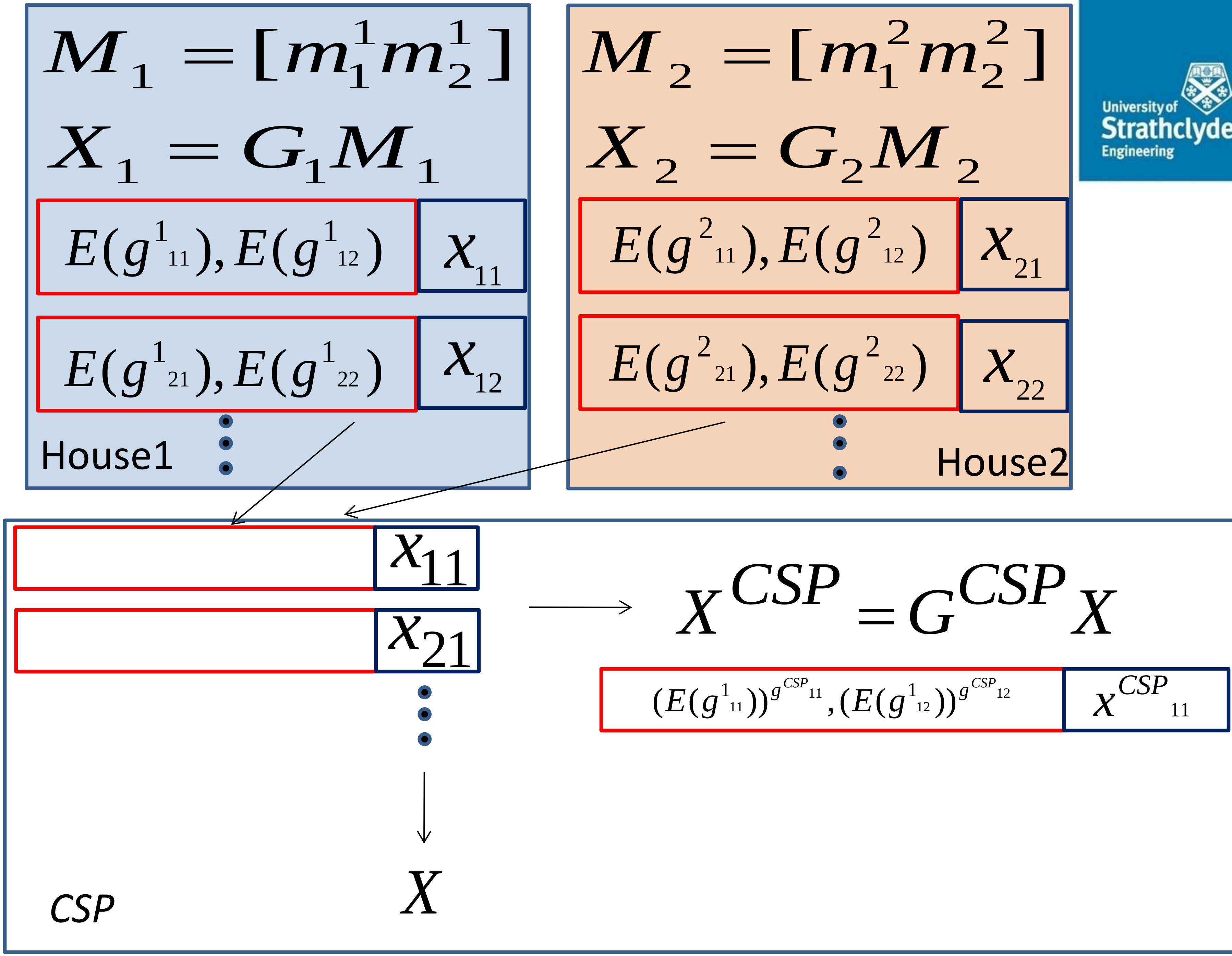
- Each house SM system performs NC on its HAN dataset
- The local encoding vectors used are then encrypted using the public key

$$c_i(e) = E_{ek}(g_i(e)), (1 \leq i \leq h)$$
$$c(e) = [c_1(e), c_e(e), \cdots, c_h(e)]$$

- CSP performs conventional NC on all incoming encoded and encrypted packets from the houses

$$g(e) = \sum_{i=1}^{h} \beta_i(e) g(e'_i)$$

$$E_{ek}\big(g(e)\big) = E_{ek}\Big(\sum_{i=1}^{h} \beta_i(e) g(e'_i)\Big)$$
$$= \prod_{i=1}^{h} E_{ek}(\beta_i(e) g(e'_i))$$
$$= \prod_{i=1}^{h} E_{ek}^{\beta_i(e)}(g(e'_i))$$



$M_1 = [m_1^1 m_2^1]$
$X_1 = G_1 M_1$
$E(g^1_{11}), E(g^1_{12})$
x_{11}
$E(g^1_{21}), E(g^1_{22})$
x_{12}
House1
$M_2 = [m_1^2 m_2^2]$
$X_2 = G_2 M_2$
$E(g^2_{11}), E(g^2_{12})$
x_{21}
$E(g^2_{21}), E(g^2_{22})$
x_{22}
House2
x_{11}
x_{21}
$X^{CSP} = G^{CSP} X$
$(E(g^1_{11}))^{g^{CSP}_{11}}, (E(g^1_{12}))^{g^{CSP}_{12}}$
x^{CSP}_{11}
X
CSP

Proposed Scheme – Decoding & Decryption at Sink

- DCC/sink will first decrypt NC coefficients
- Resulting global encoding vectors are used for RLNC decoding in the conventional way, e.g., using Gaussian elimination
- Note that all houses have knowledge of the public key and only the DCC has knowledge of the private key for decryption
- At the sink decryption can be carried out once a sufficient number of packets from the same generation has been received
- $$\begin{bmatrix} x_1 \\ \vdots \\ x_h \end{bmatrix} = G^{-1} \begin{bmatrix} x^{csp}(e_1) \\ \vdots \\ x^{csp}(e_h) \end{bmatrix}$$

$$(E(g^{1}{}_{11}))^{g^{CSP1}{}_{11}}, (E(g^{1}{}_{12}))^{g^{CSP1}{}_{12}} \quad x^{CSP1}{}_{11}$$

$$(E(g^{1}{}_{11}))^{g^{CSP2}{}_{11}}, (E(g^{1}{}_{12}))^{g^{CSP2}{}_{12}} \quad x^{CSP2}{}_{11}$$

$\vdots$

Decrypt encoding coefficients

$$D((E(g^{1}{}_{11}))^{g^{CSP1}{}_{11}}) = g^{CSP1}{}_{11} g^{1}{}_{11}$$

Gaussian Elimination for NC decoding

$\overline{M}$ Recovered message

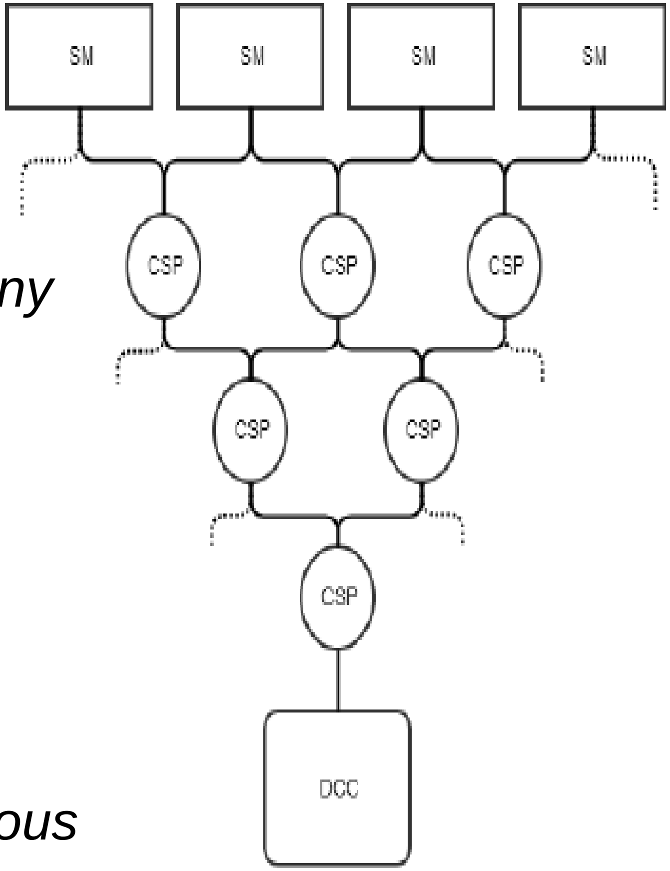
DCC

Analysis

- Is efficient and does not incur a significantly high overhead
- Features privacy against packet analysis
- Encryption prevents against earliest decoding by packet analysis
- Each message is of the same size helping prevent size correlation and buffering reduces effect of time order correlation attacks
- Inefficient against Pollution and Entropy attacks

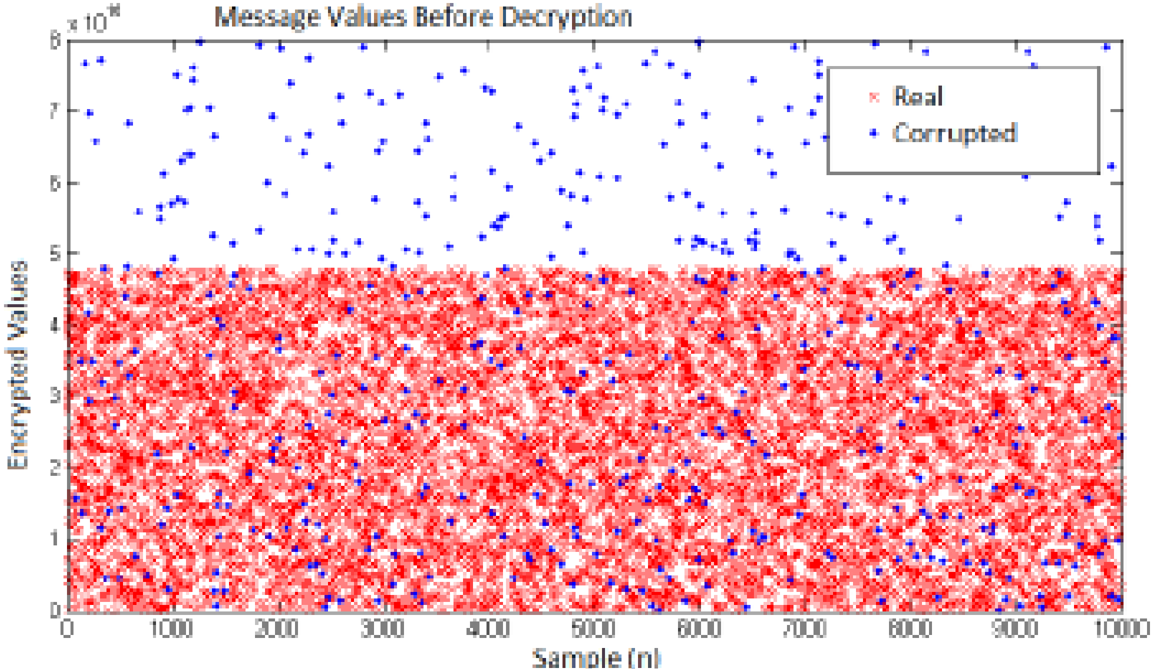
Resilience to packet drops

- CSPs dropping incoming packets
- RLNC provides erasure protection, and additional PHE does not affect erasure protection of RLNC
- Lemma1: *If only one CSP is dropping all packets it receives, then all messages from any house can be recovered at the DCC*

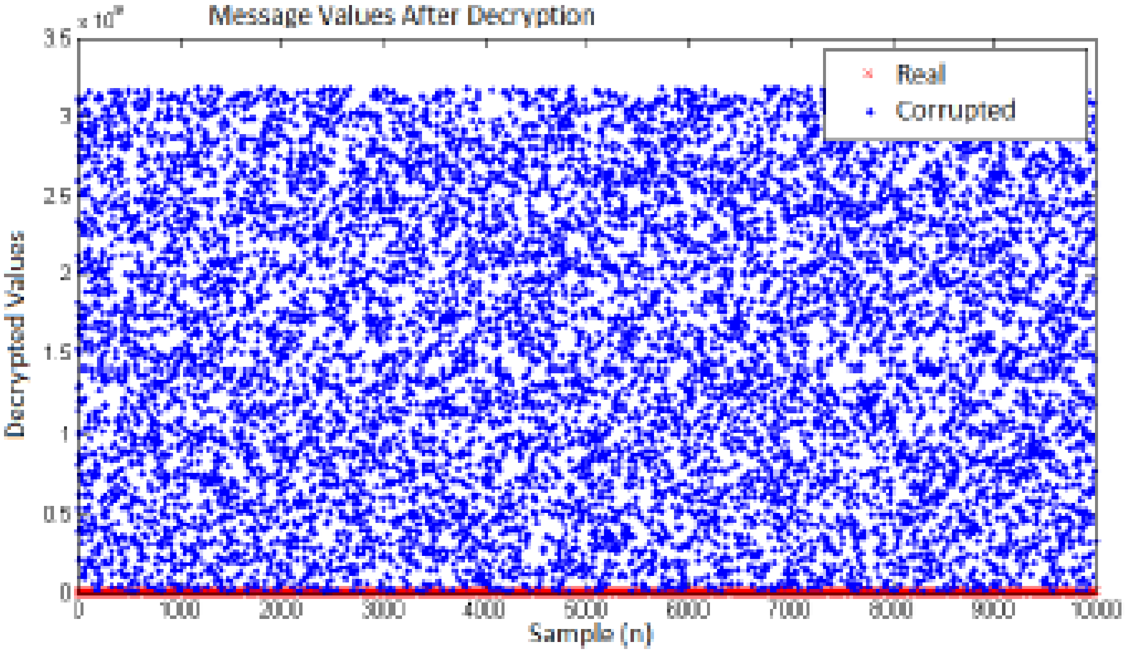


Pollution and entropy attacks

- Attacker injects dummy packets
- CSP can generate malicious content that is mixed with incoming packets
- Lemma2: *If only one CSP is injecting malicious content and mixing it with incoming packets, then all messages from any house can be recovered at the DCC*

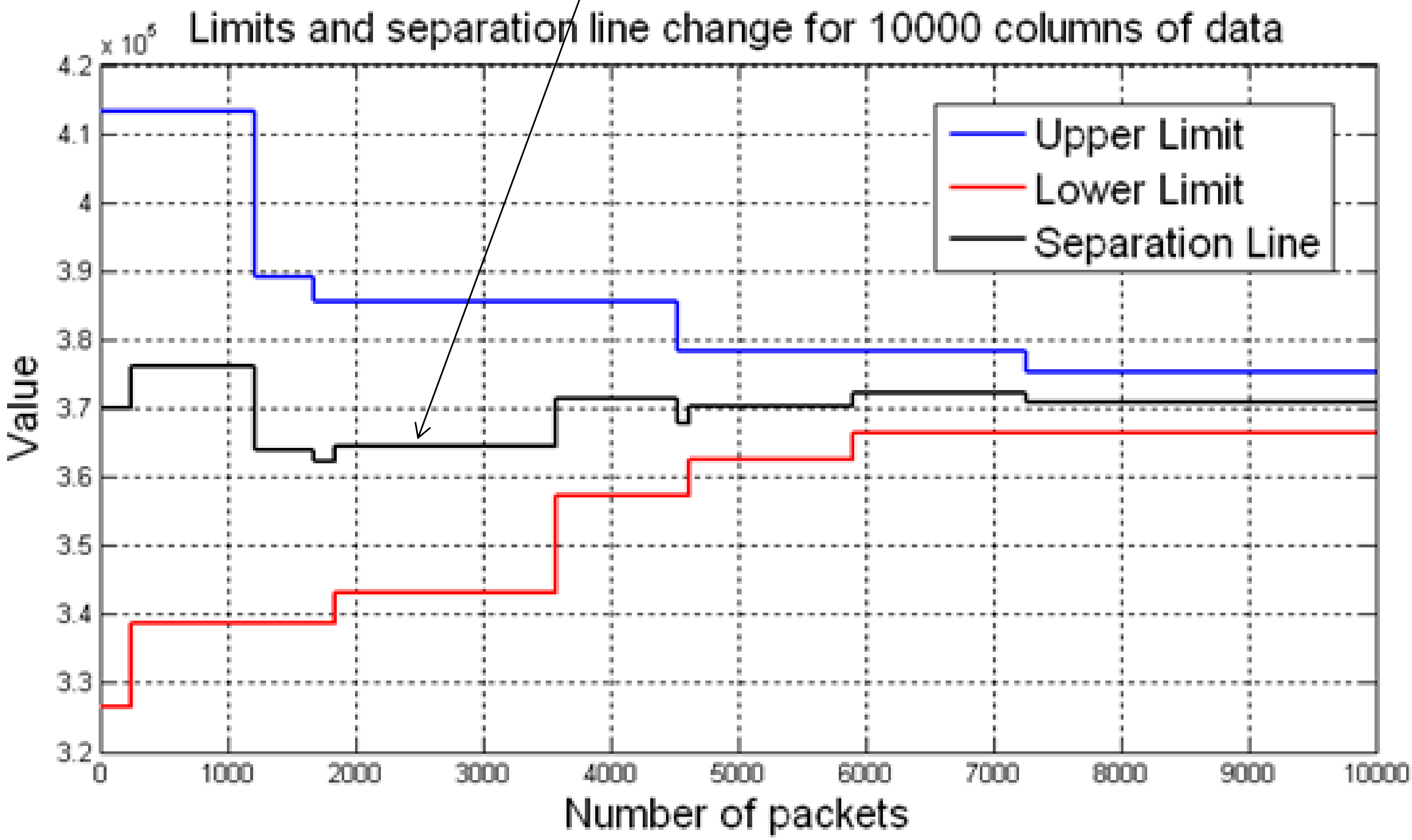


before decryption



after decryption =>
Clear separation between corrupted and useful packets

Adaptive threshold to separate corrupted/injected packets from the original ones



Computational Overhead

- Communications Hub (SM) encoding:
  - PHE: $O(N^2)$
  - Multiplications & modulus operations: $O(N^2 logn)$

- CSP encoding:
  - Per packet $O(N^2 \log n)$
  - Total: $O(N^3 \log n)$

- DCC decoding:
  - $O(N^2 \log n)$

Conclusions

- With smart meter rollouts being deployed worldwide, it is critical to ensure secure transmission of sensitive personal data that is subject to eavesdropping and malicious attacks.

- We propose a combined homomorphic encryption algorithm with network coding that provides security and privacy while maintaining RLNC allowing for a high chance of recovering packets at the sink.

- Open work:
  - Implementation of lightweight verification scheme to prevent pollution attacks propagating throughout the network
  - Assessing robustness to a large scale attacks
  - Practical implementation

Acknowledgements

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University of Strathclyde Engineering

- All presented work is being addressed as part of two UK Research Council projects by our team, within multi-disciplinary and multi-institutional (academic + industrial) consortiums
  - REFIT: Personalised Retrofit Decision Support Tools for UK Homes using Smart Home Technology
  - APAtSCHE: Aging Population Attitudes to Sensor Controlled Home Energy

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