Privacy-Enhanced Bi-Directional Communication in the Smart Grid using Trusted Computing

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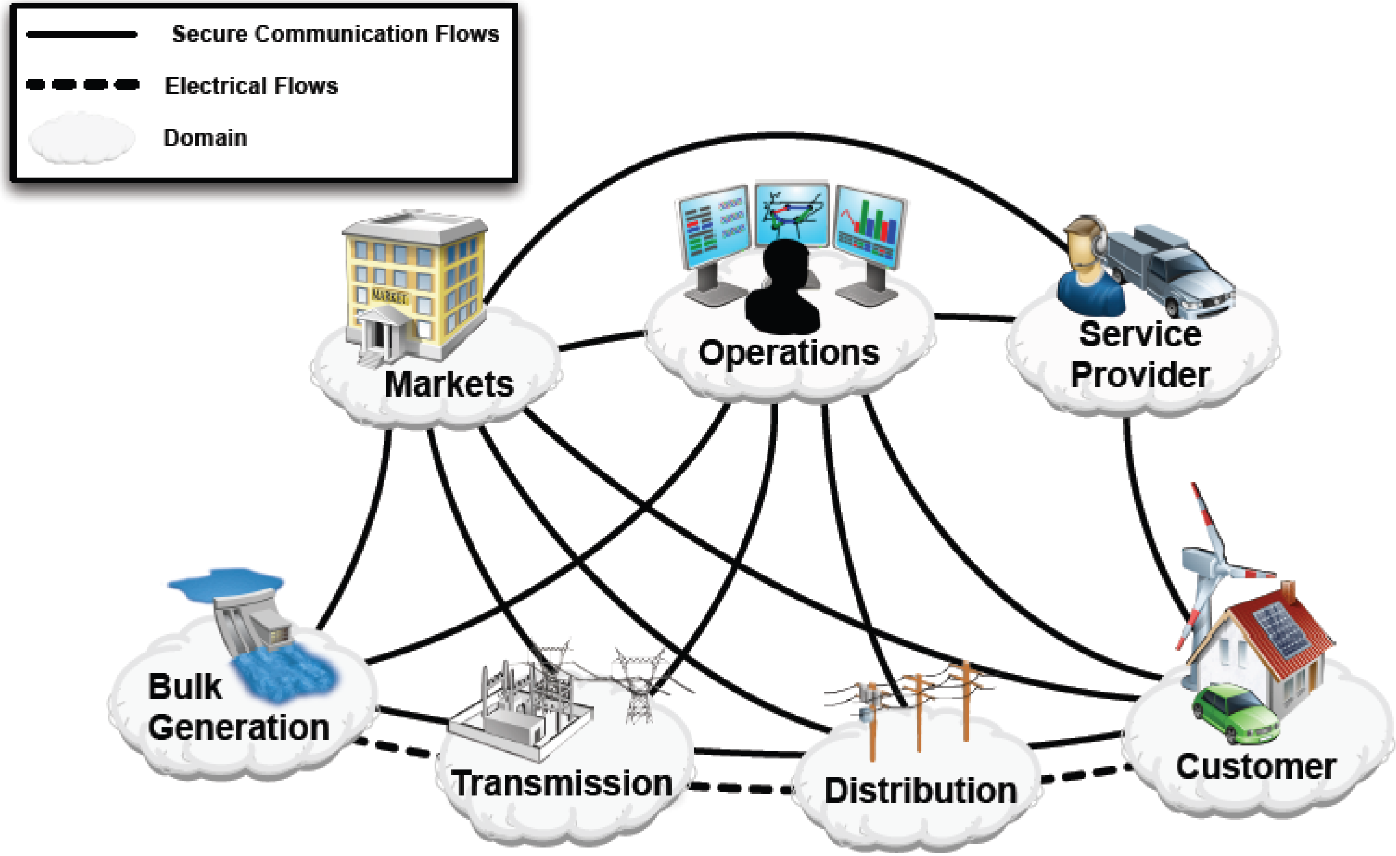
Smart Grid Architecture

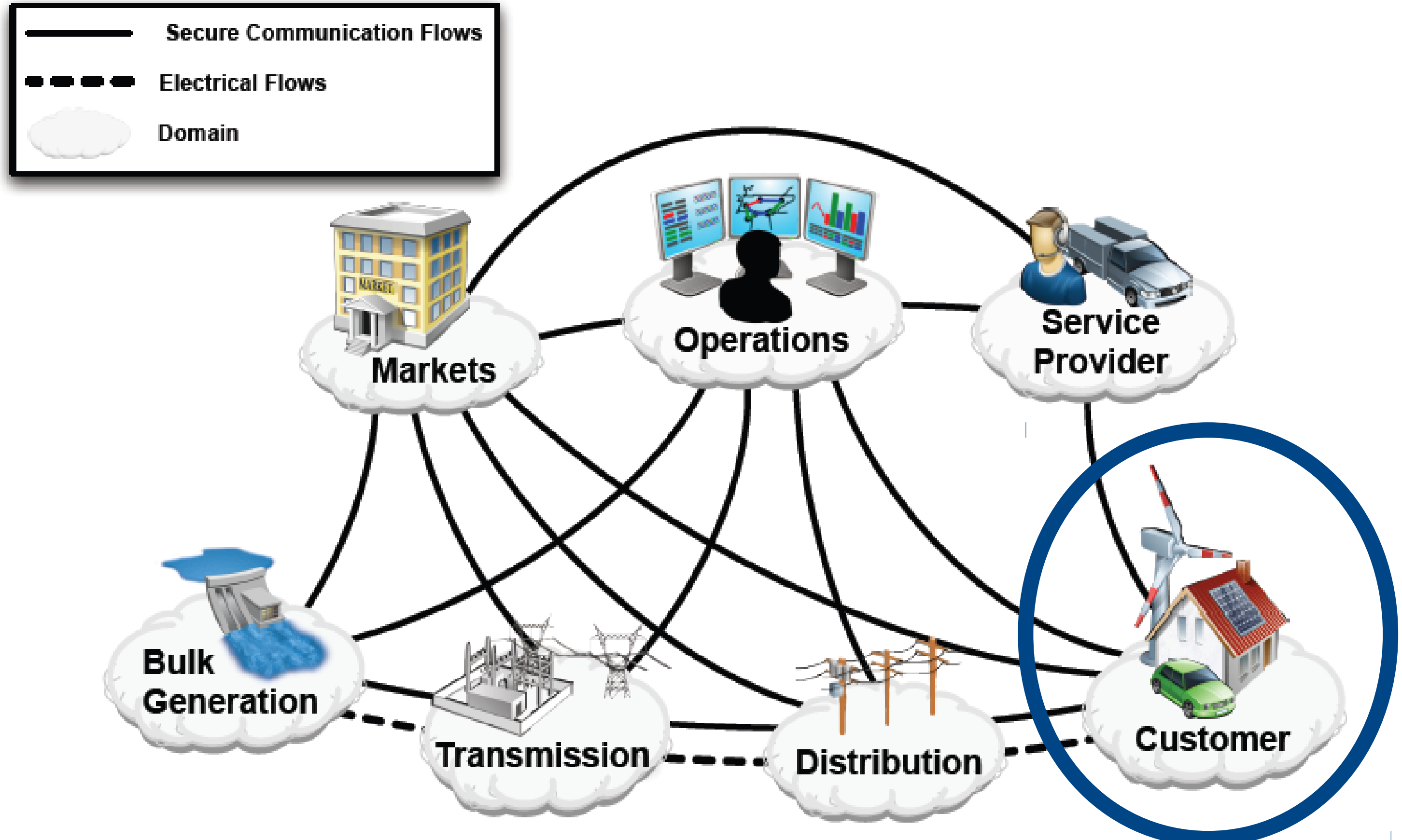
NIST Model



NIST Smart Grid Framework

Smart Grid Architecture

NIST Model



NIST Smart Grid Framework

Information Flows

1. Monitoring

- Monitoring/balancing specific sectors
- Unidirectional: smart meters → DNO/supplier
- Requires high temporal granularity but can be spatially aggregated

2. Billing

- Facilitates dynamic energy pricing
- Unidirectional: smart meters → energy supplier
- Requires individual data but can be temporally aggregated

Demand Response (DR)

→ Incentive Based Programs (IBP) → Classical → Direct Control → Interruptible/Curtailable Programs → Market Based → **Demand Bidding** → Emergency DR → Capacity Market → Ancillary services market	→ Price Based Programs (PBP) → **Time of Use (TOU)** → Critical Peak Pricing (CPP) → Extreme Day CPP (ED-CPP) → Extreme Day Pricing (EDP) → **Real Time Pricing (RTP)**

Classification of demand response programs (Albadi et al.)

Information Flows

1. Monitoring

2. Billing

3. Demand Response (DR)

- Demand-bidding and equivalent protocols
- “Transactive” energy markets
- Closed-loop feedback control
- Requires full bi-directional communication:
    - Consumers ↔ Demand Side Manager (DSM)

Security and Privacy Threats

Security Threats

- Modification or falsification of data

Privacy Threats

- Honest-But-Curious (HBC) adversary
- Inference of private information
  - Non-Invasive Load Monitoring (NILM)

These are applicable to all three information flows

- Paverd et al. “Security and Privacy in Smart Grid Demand Response Systems,” *SmartGridSec14*.

Existing Solutions

1. Monitoring

- Spatial aggregation (Garcia et al.)
- Pseudonymization (Rottondi et al.)

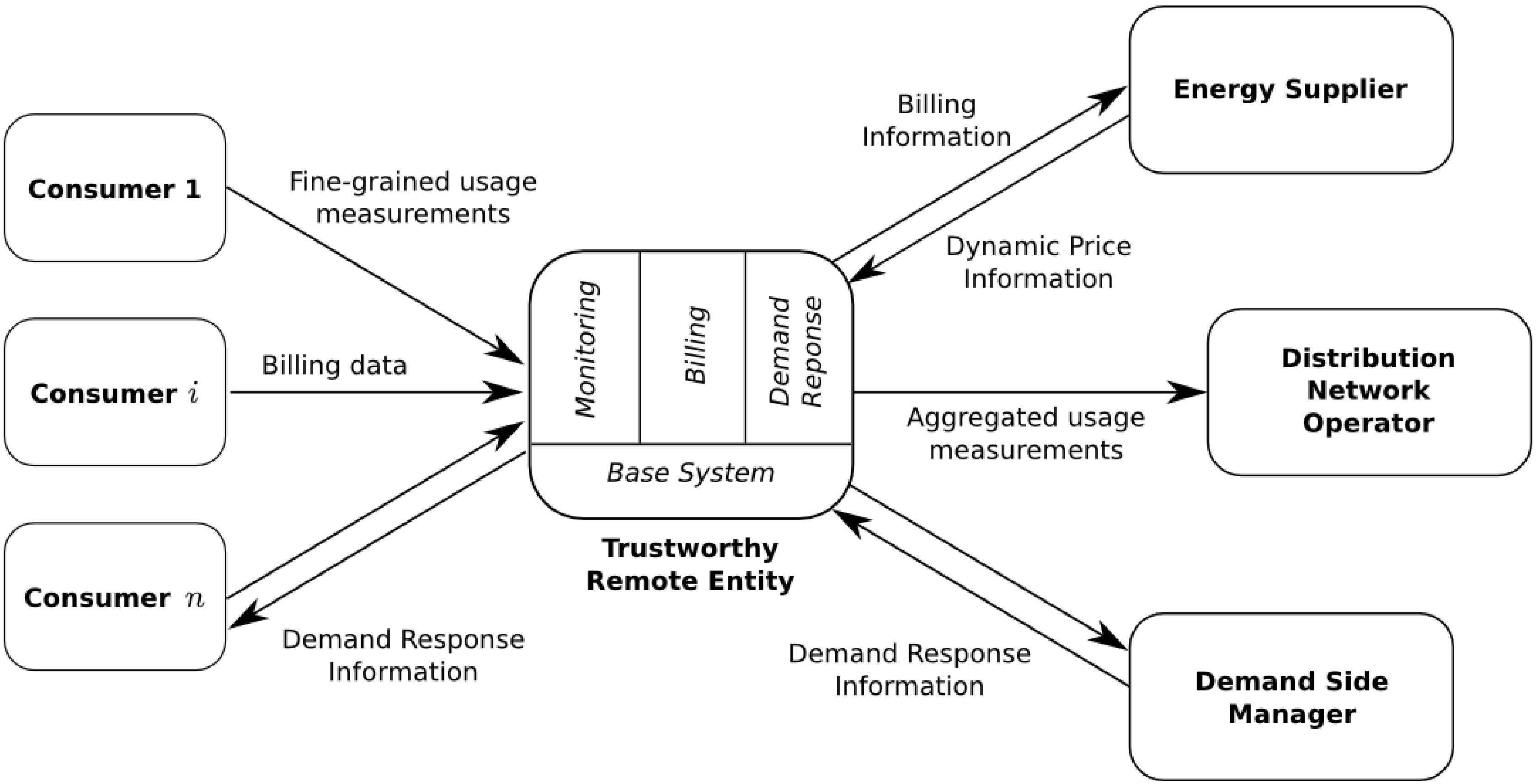
2. Billing

- Temporal aggregation (Danezis et al.)

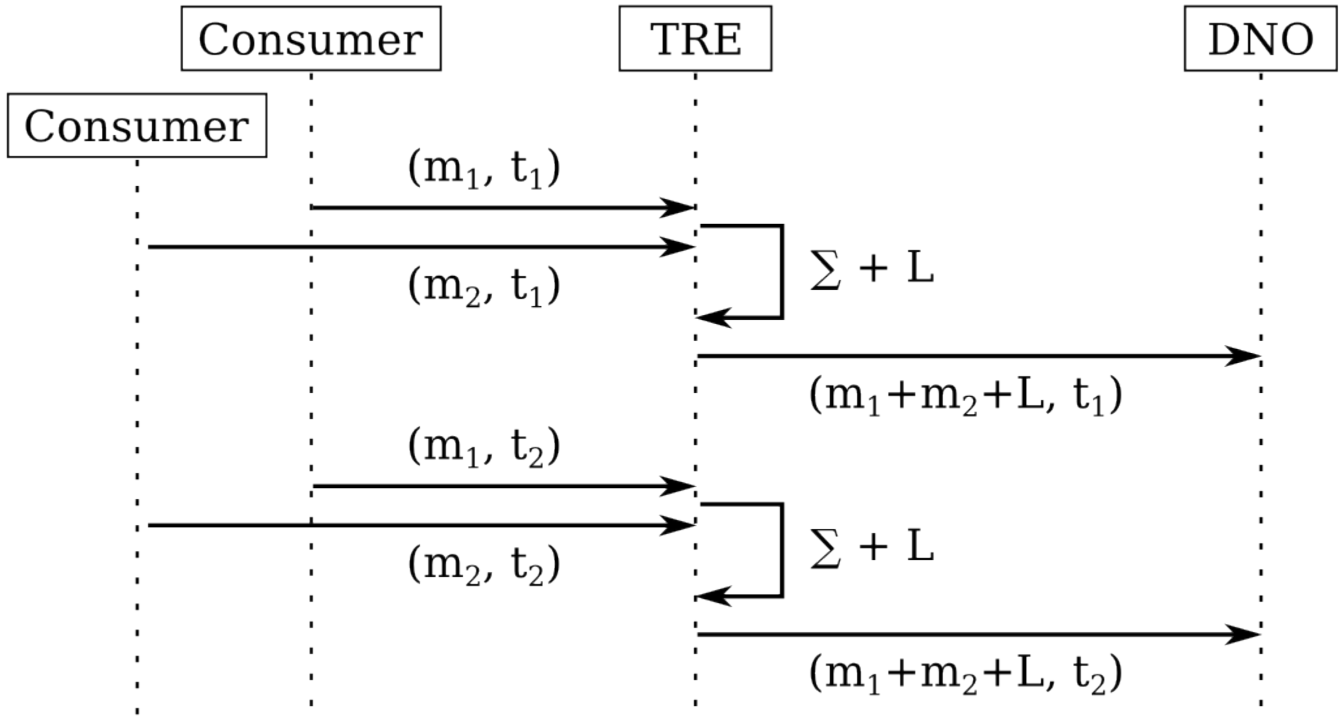
3. Demand Response

- Cannot aggregate bi-directional communication

Trustworthy Remote Entity (TRE)

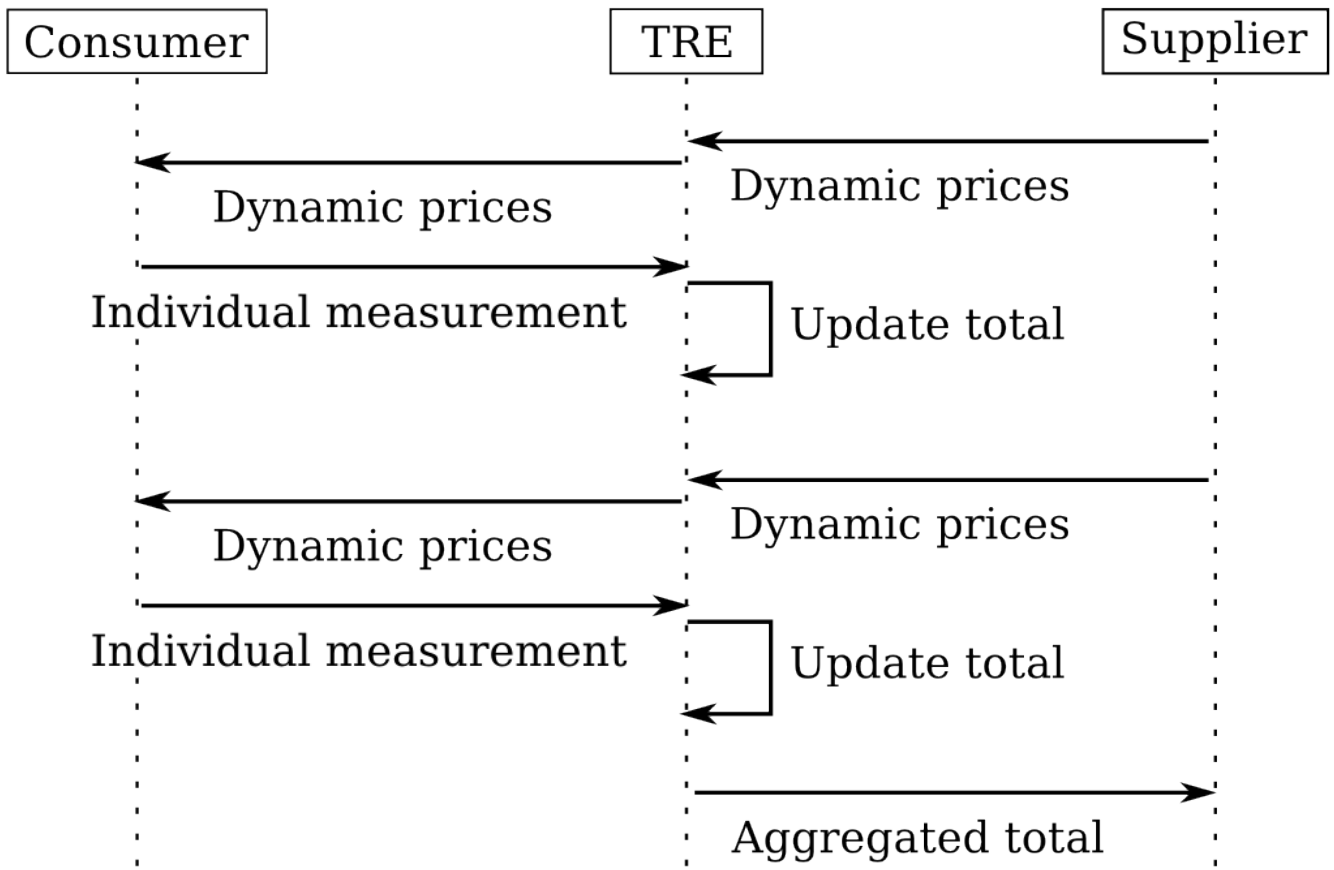


Monitoring



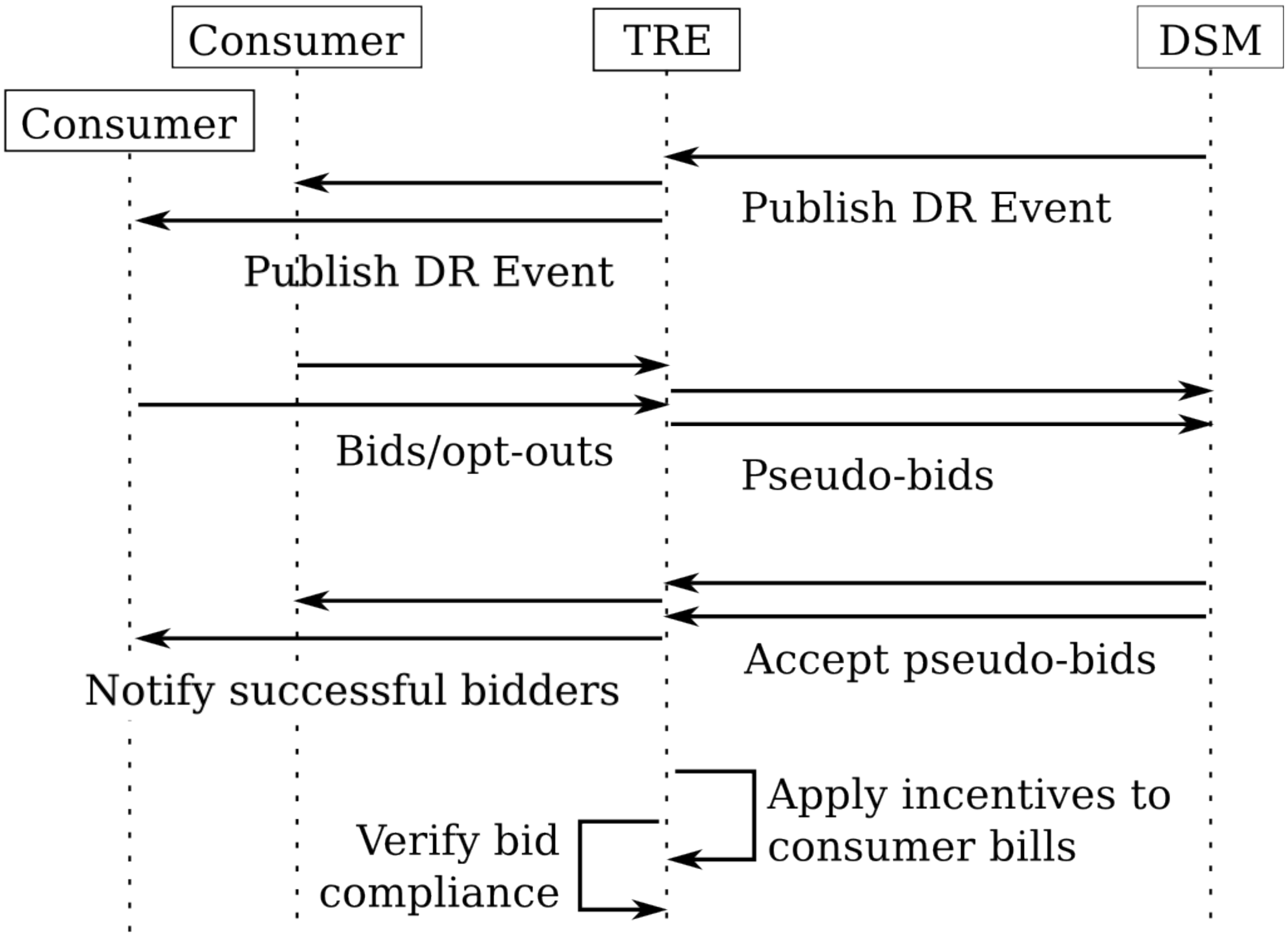
Differential Privacy (Dwork et al.) $L \sim \mathrm{Lap}(1/\varepsilon)$

Billing

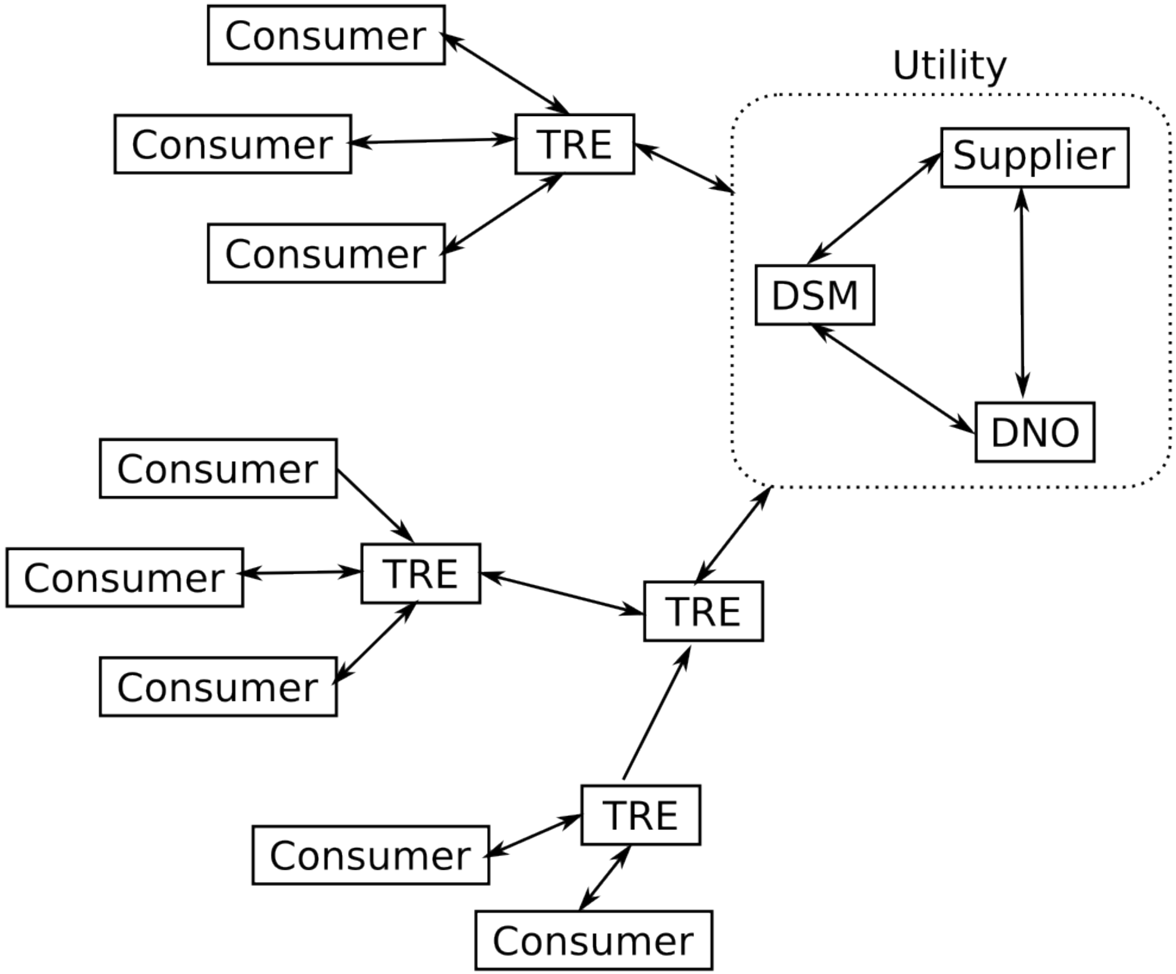


Consumer
TRE
Supplier
Dynamic prices
Dynamic prices
Individual measurement
Update total
Dynamic prices
Dynamic prices
Individual measurement
Update total
Aggregated total

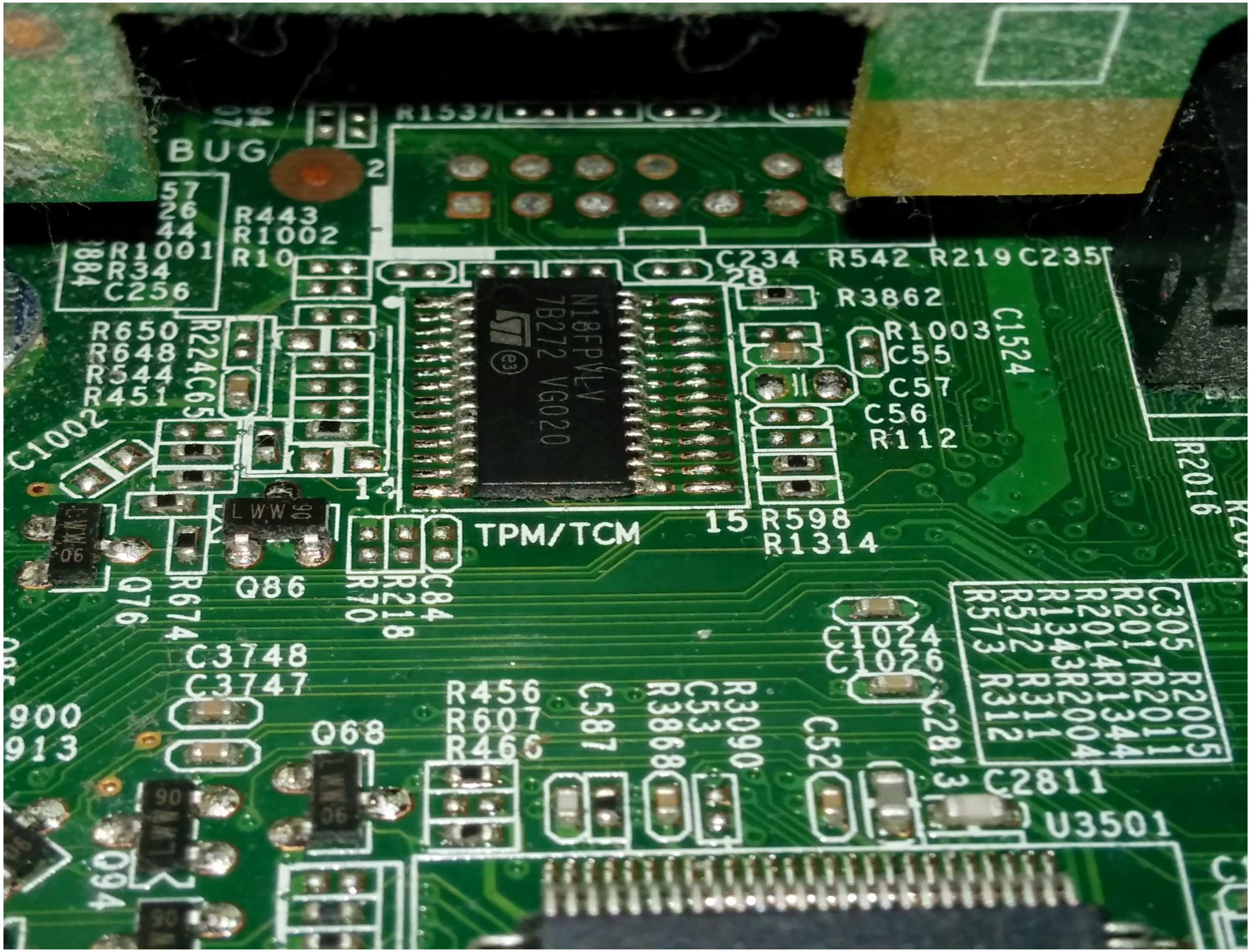
Demand Bidding



Enhanced Architecture



Establishing Trust



Establishing Trust

Trusted Platform Module (TPM)

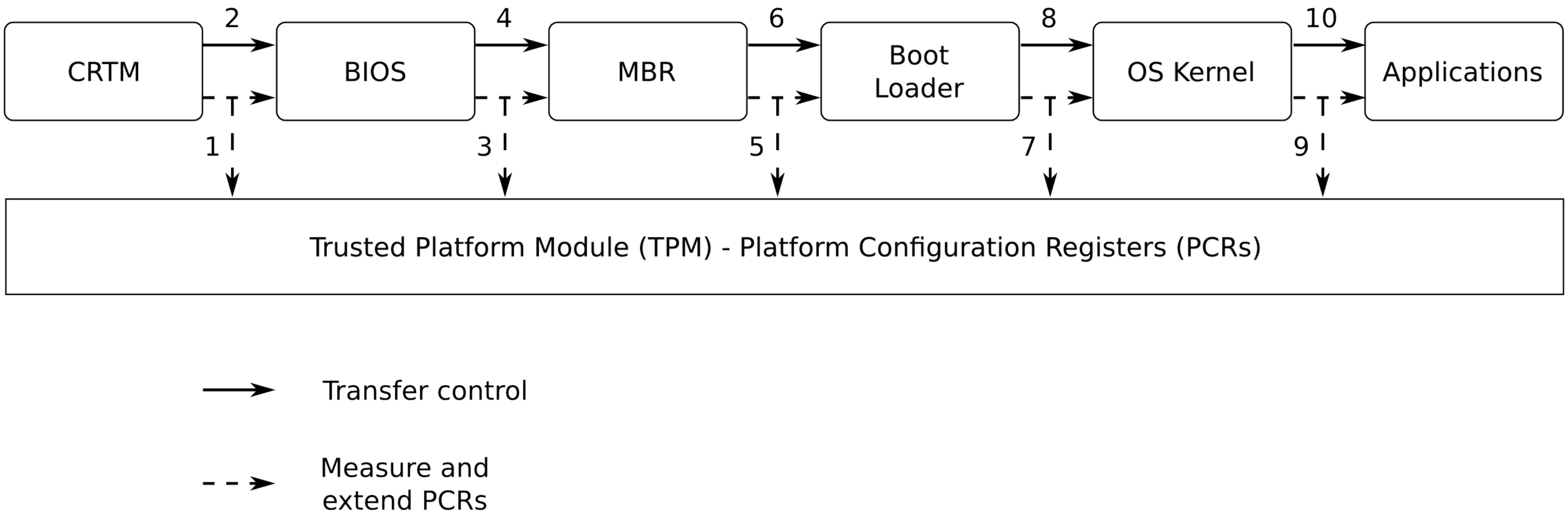
- Standardized by the Trusted Computing Group (TCG)
- Widely-deployed cryptographic co-processor
  - Over 500 million TPMs deployed
  - FIPS 140-2 certified
- Hardware random number generator
- Secure storage of private keys
- Extend-only Platform Configuration Registers (PCRs)

$$pcr_0 := 00000000000000000000$$

$$pcr_{k+1} := \text{sha1}(\, pcr_k \,||\, \text{new value} \,)$$

Establishing Trust

Measured Boot



Establishing Trust

Remote attestation

- Cryptographic proof of PCR values
- Scalability challenges on modern systems due to quantity of software.

```
verifier → prover:   nonce
prover → verifier:   pcrs, signature(pcrs, nonce)
```

Establishing Trust

Trustworthy Remote Entity (TRE)

- Single-function, specialized system
  - Networking, crypto, TPM & protocol logic
  - Uses measured boot and remote attestation
- Orders of magnitude less code than OS kernel
  - Linux kernel 3.10 ~15,000 kLoC
  - TRE ~20 kLoC
- Micro-benchmarks
  - Remote attestation: ~700 ms per operation
  - > 1000 attestations per 15 minutes

Formal Analysis

***Casper/FDR* tool (Lowe et al.)**

- Describe protocols in user-friendly script
- Compile description into CSP model
- Analyses secrecy and authentication properties
- Uses the Dolev-Yao adversary model

***Casper-Privacy* tool (Paverd et al.)**

- Uses existing Casper/FDR script and model
- Adds privacy properties: undetectability & unlinkability
- Uses the Honest-But-Curious (HBC) adversary model

Formal Analysis

```
#Protocol description
1.  sma -> tre : sma, ma1
1b. smb -> tre : smb, mb1
2.  tre -> ut  : agg1
3.  sma -> tre : sma, ma2
3b. smb -> tre : smb, mb2
4.  tre -> ut  : agg2
5.  tre -> ut  : sma, agga
5b. tre -> ut  : smb, aggb

#Specification
Secret(sma, ma1, [tre])
Secret(sma, ma2, [tre])
Agreement(sma, tre, [ma1, ma2])
Agreement(tre, ut,  [agg1, agg2])
Agreement(tre, ut,  [agga, aggb])

#Privacy
Unlinkable( UT, {MA1,SMA} )
Unlinkable( UT, {MB1,SMB} )
Unlinkable( UT, {MA2,SMA})
Unlinkable( UT, {MB2,SMB} )
```

Formal Analysis - Security

Security properties:

- Only authorized consumers can submit measurements and DR bids [false data injection attacks]
- Consumers cannot submit multiple measurements in a single period [false data injection attacks]
- Unauthorized modifications of measurements or bids are detected [false data injection attacks]
- Consumers cannot impersonate each other [fraud]

Formal Analysis - Privacy

Privacy properties:

- Measurements and bids cannot be viewed by external adversaries [confidentiality]
- Only the TRE can detect if a specific consumer has placed a DR bid [undetectability]
- Measurements, bids and DR incentives cannot be linked to individual consumers except by the TRE [unlinkability]

Conclusions

- Demand Bidding requires full bi-directional communication between consumers and DSM.
- Privacy-preserving bi-directional communication is possible with the use of a TRE.
- Trusted Computing remote attestation can provide proofs of trustworthiness for the TRE.
- The security and privacy properties of the protocols can be analysed using formal methods.

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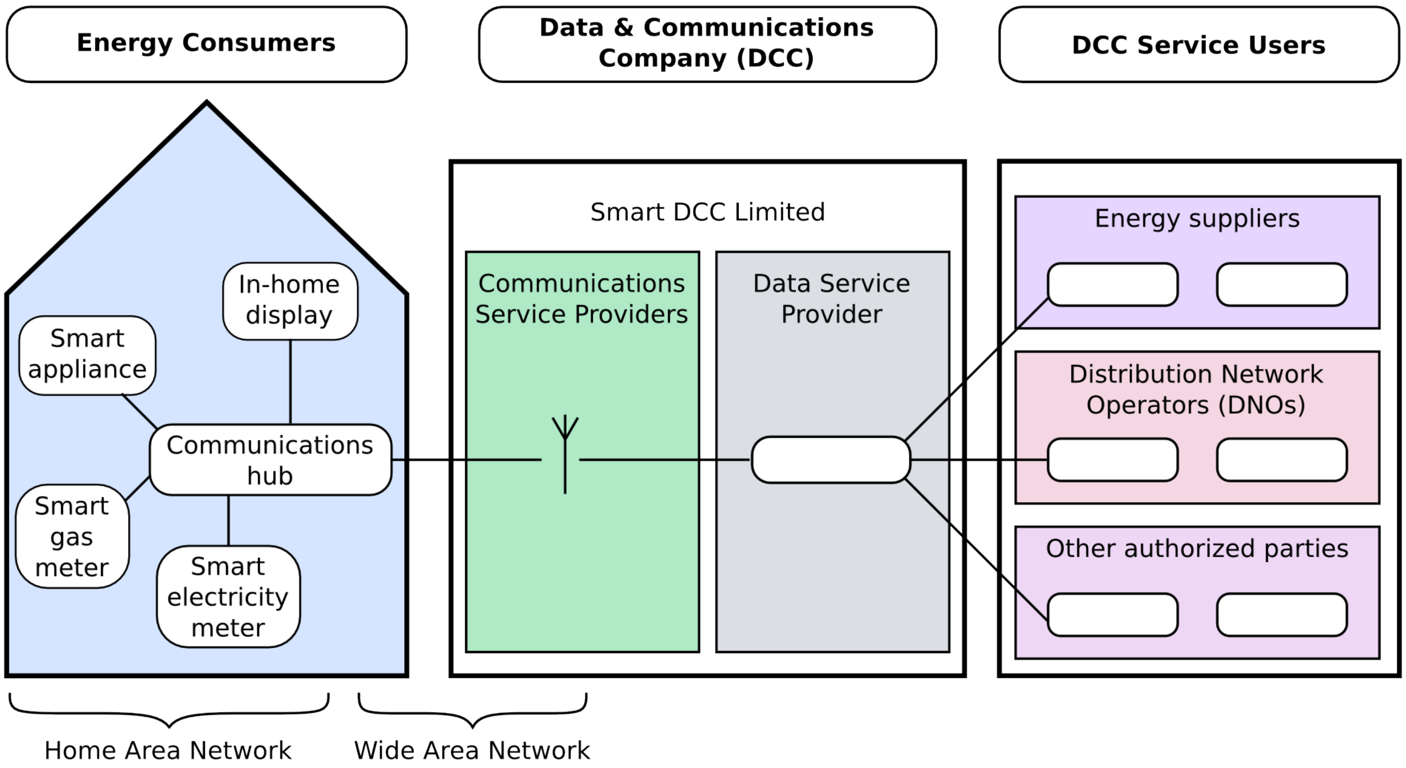
Demand Response

“Changes in electric usage by end-use customers from their normal consumption patterns in response to changes in the price of electricity over time, or to **incentive payments** designed to induce lower electricity use at times of high wholesale market prices or when system reliability is jeopardized”

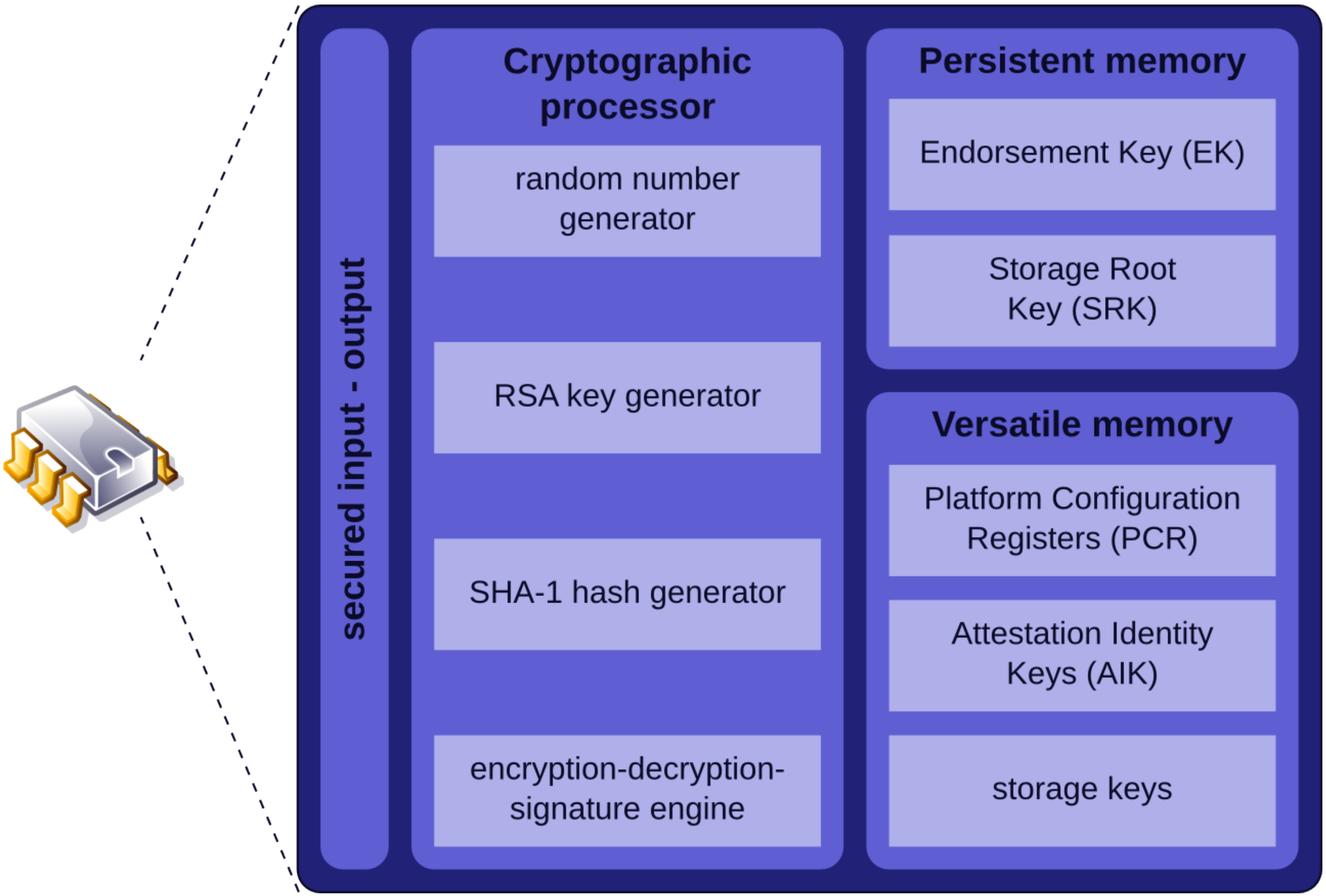
- United States Department of Energy

Smart Grid Architecture (GB)

GB Model



Trusted Platform Module



"TPM" by This figure was made by Eusebius (Guillaume Piolle).