On Privacy-Preserving Protocols for Smart Metering Systems

UFRJ/COPPE

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Coordenação de Sistemas e Redes (CSR)

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Privacy-Preserving Protocols (PPPs)
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- PPP3 - Based on Asymmetric DC-Net (ADC-Net)
- PPP4 - Based on Quantum Cryptography

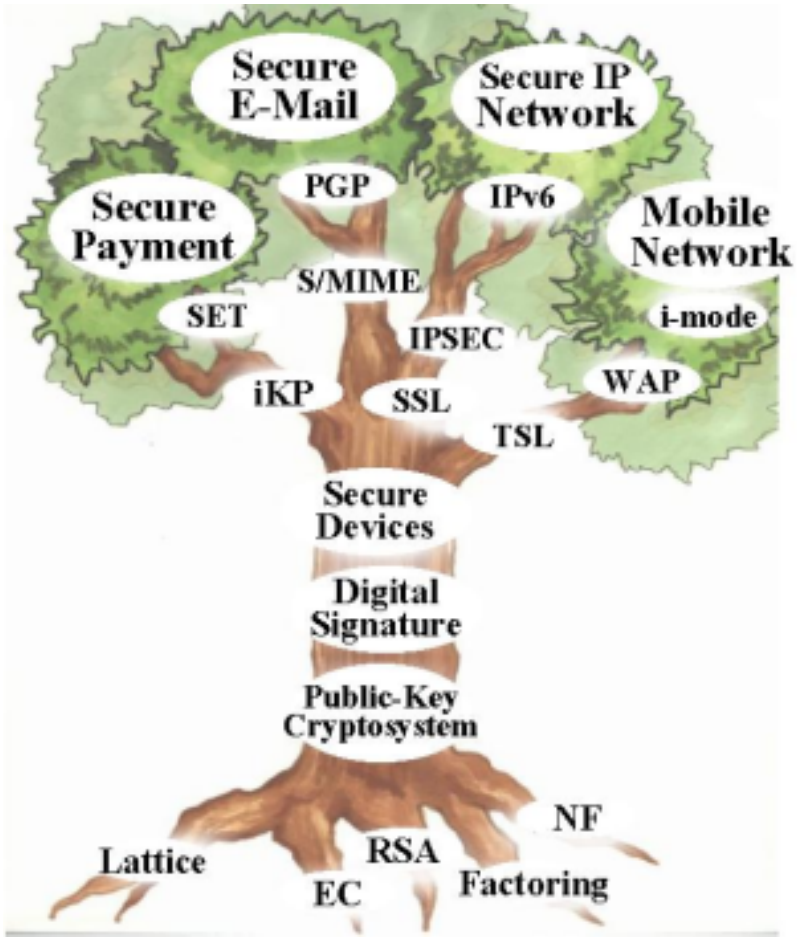
ADC-Nets

Simulation Using Real-World Data

Conclusion and Outlook

Security Tree

from bottom to top



Areas

Big Areas

- Security

Alert

Applications? Differences?

Areas

Big Areas

- Security
  - Physical Security

Alert

Applications? Differences?

Areas

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    - Malware, IDS, ...

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    - Host Security

Alert

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    - Malware, IDS, ...
    - Network Security
    - Host Security
  - Cryptography

Alert

Applications? Differences?

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    - Network Security
    - Host Security
  - Cryptography
    - Symmetric

Alert

Applications? Differences?

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    - Symmetric
    - Asymmetric

Alert

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    - Asymmetric
  - Privacy

Alert

Applications? Differences?

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    - Homomorphic Encryption

Alert

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    - DC-Nets

Alert

Applications? Differences?

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    - Host Security
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    - Symmetric
    - Asymmetric
  - Privacy
    - Homomorphic Encryption
    - DC-Nets
    - ADC-Nets

Alert

Applications? Differences?

CSR
LNCC

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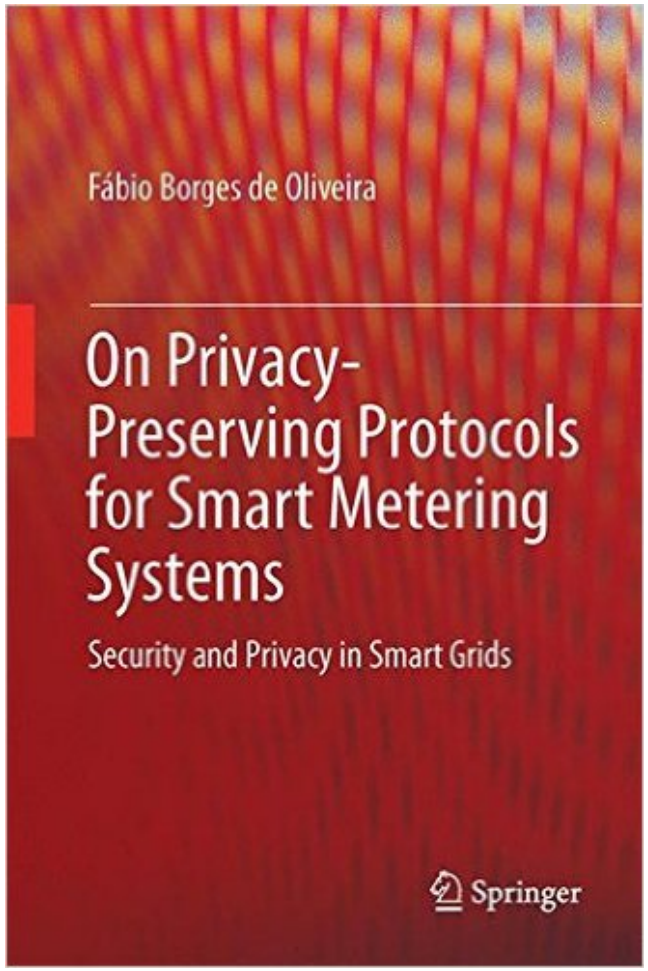
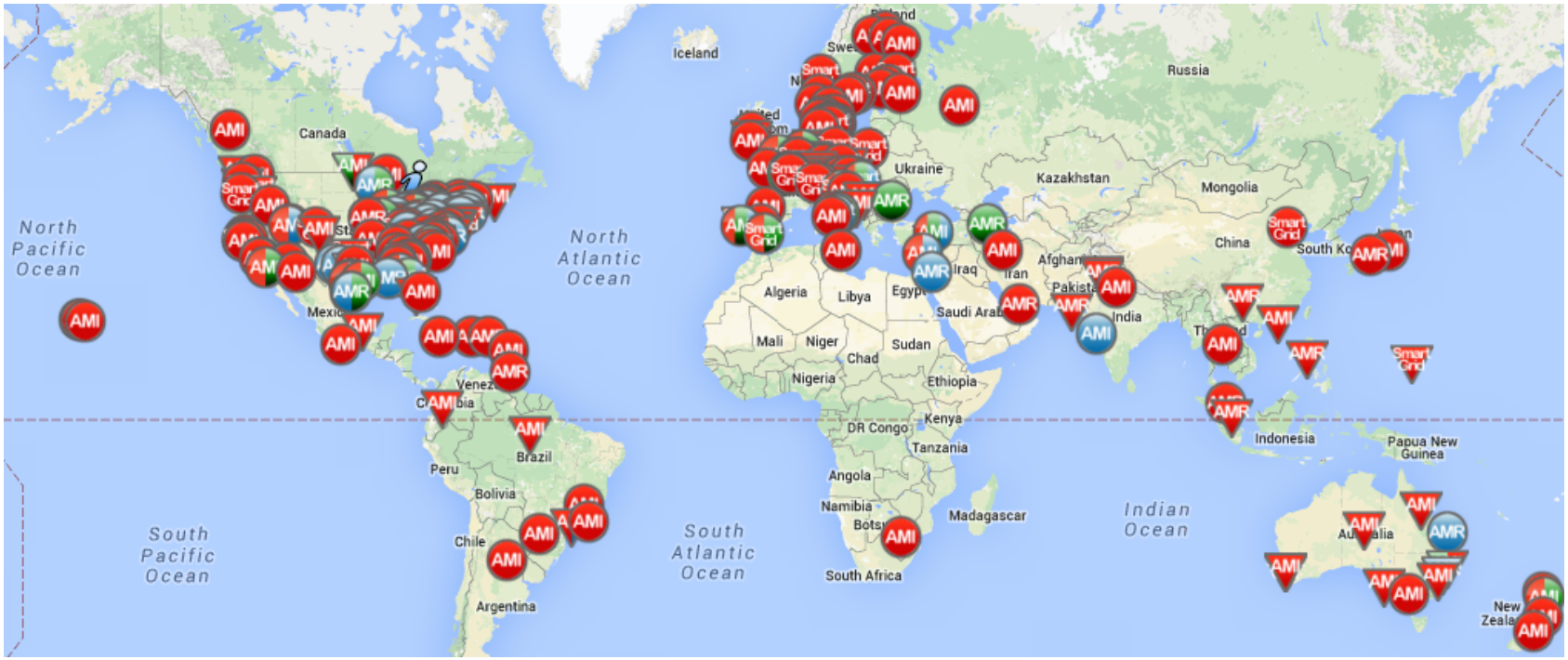
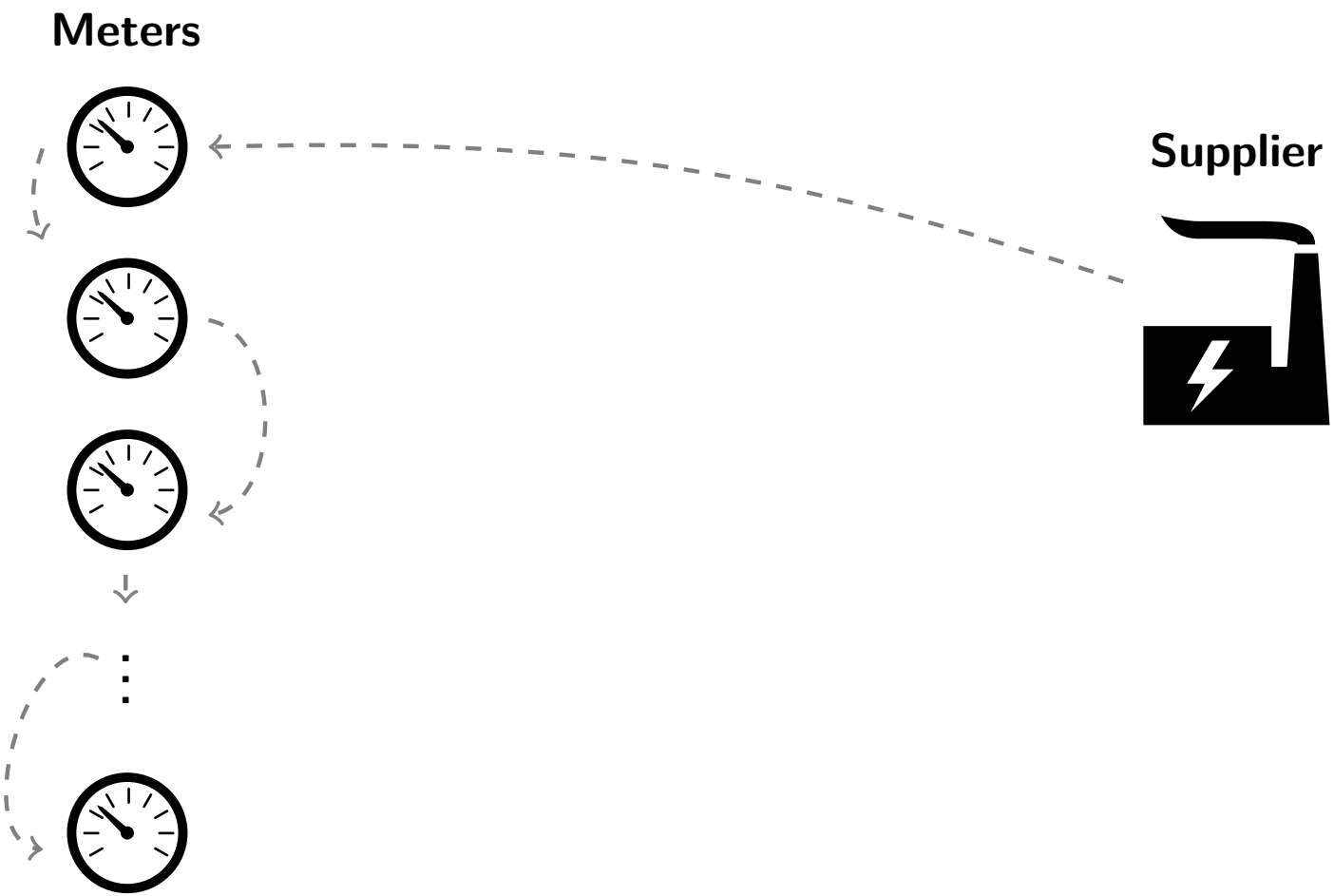

Fábio Borges de Oliveira
On Privacy-Preserving Protocols for Smart Metering Systems
Security and Privacy in Smart Grids
Springer

Smart Metering Projects Map

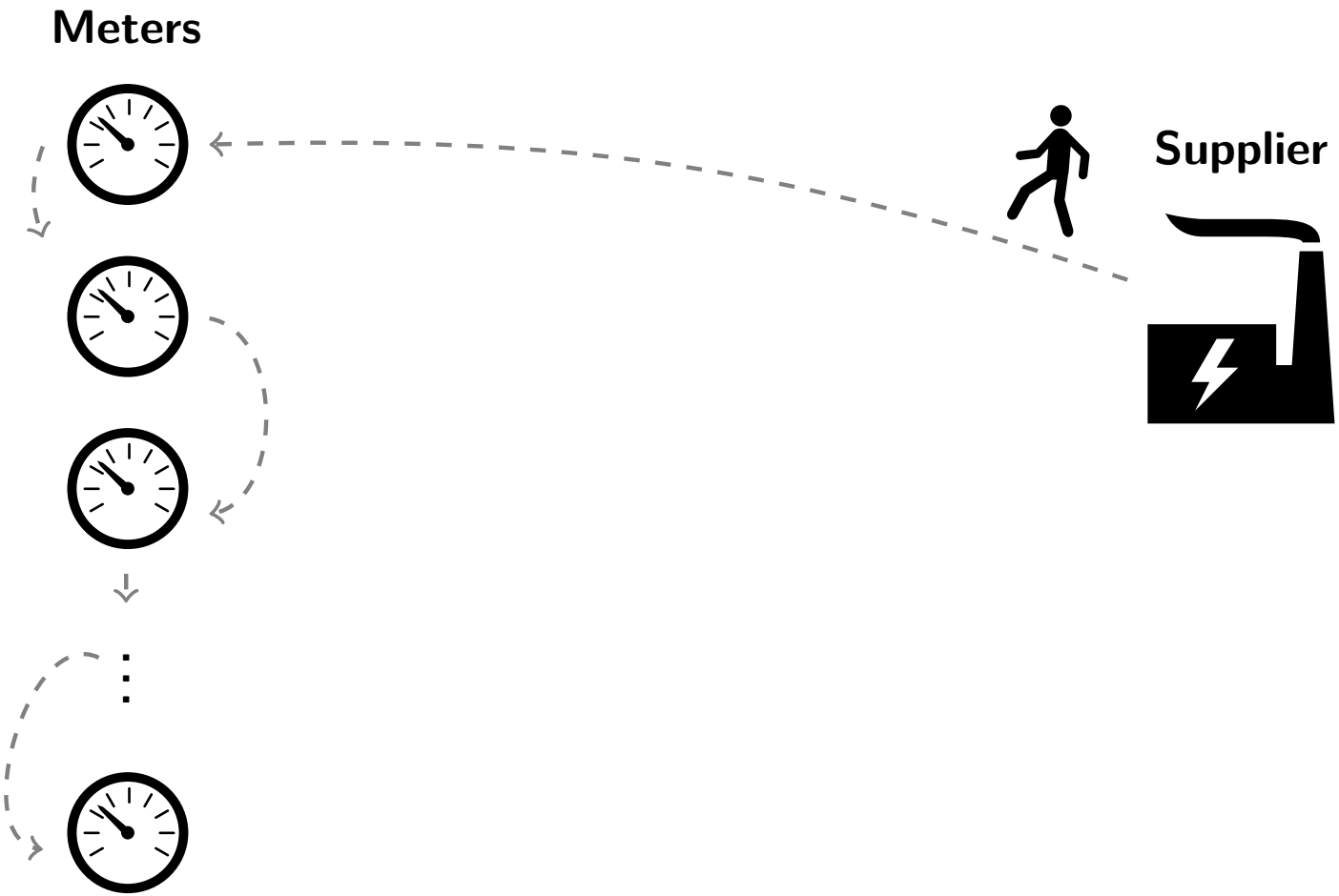
Google Maps



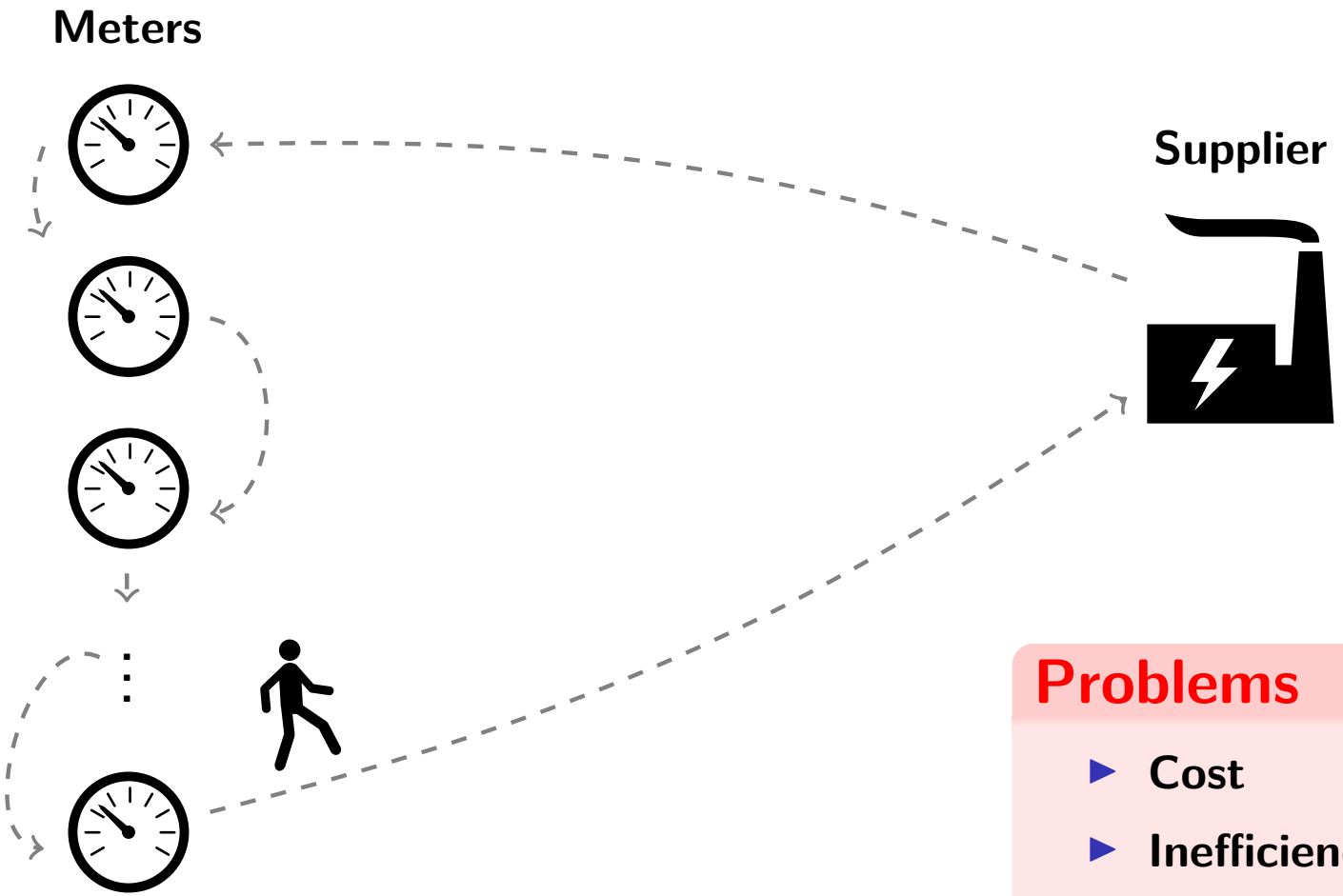
Non-smart Grid



Non-smart Grid



Non-smart Grid

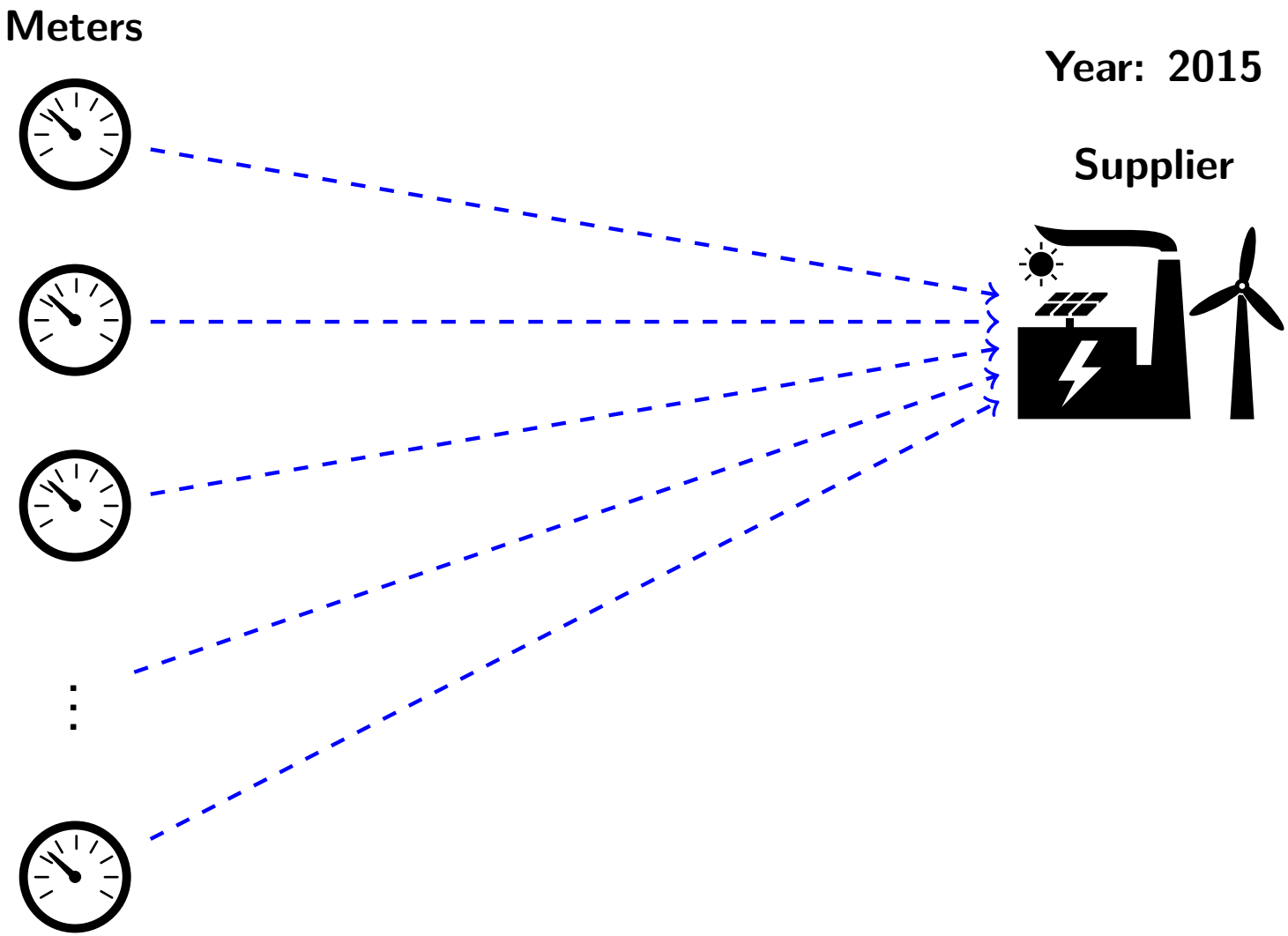


Problems

- Cost
- Inefficiency
- Fraud

Getting Smart

Collecting on a yearly basis



Getting Smart

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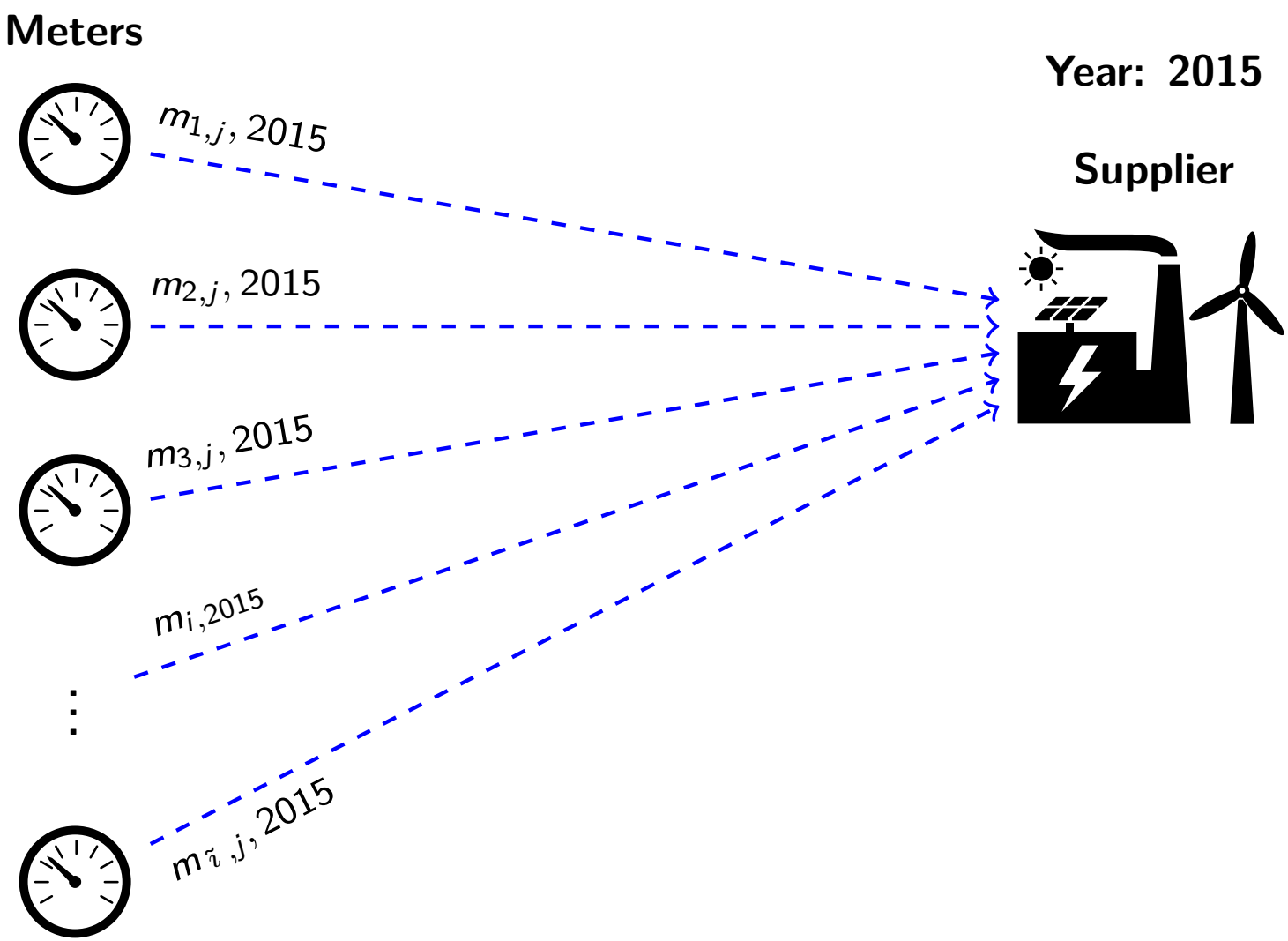

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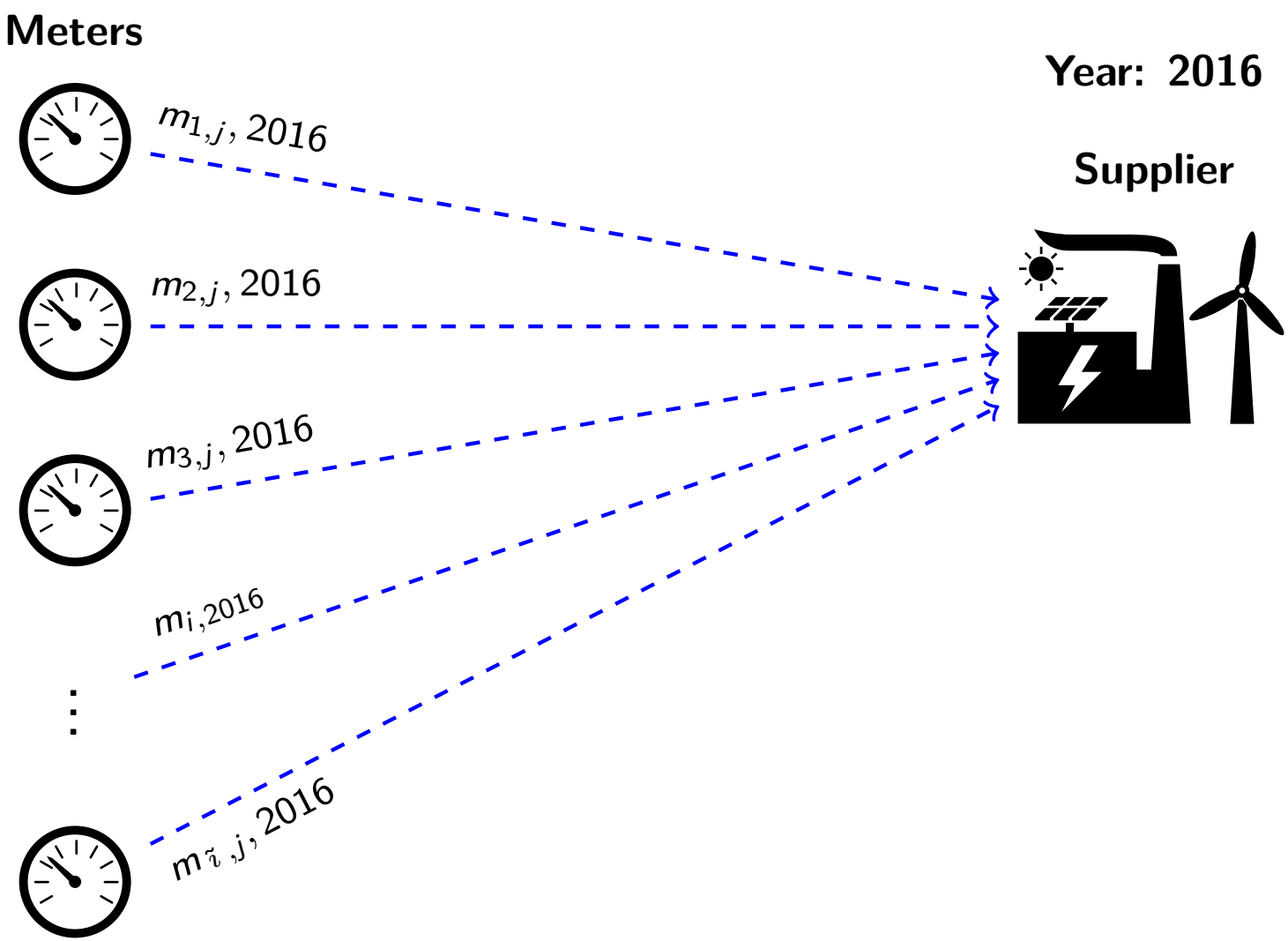
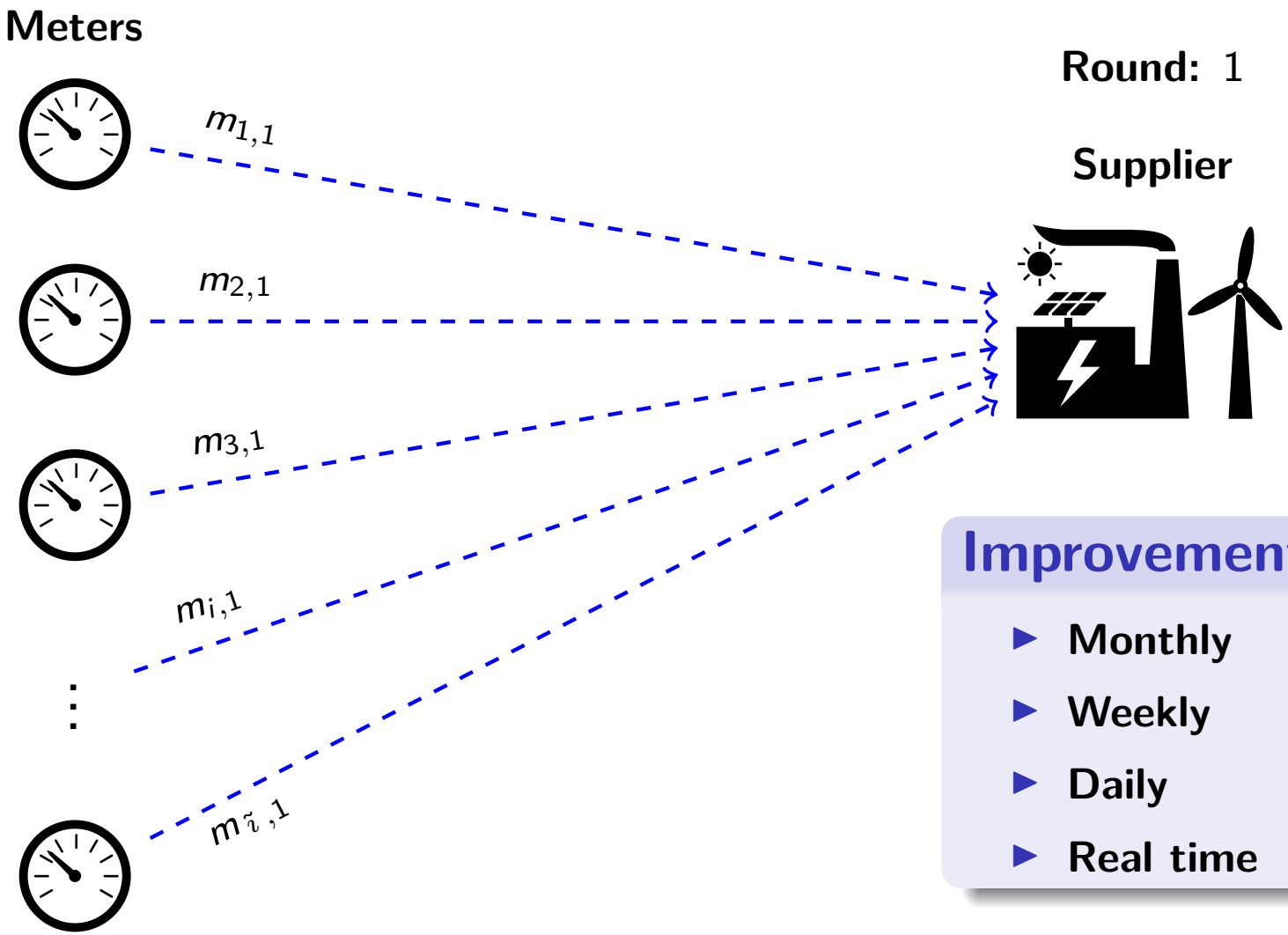
Collecting on a yearly basis



Getting Smart

Collecting per round

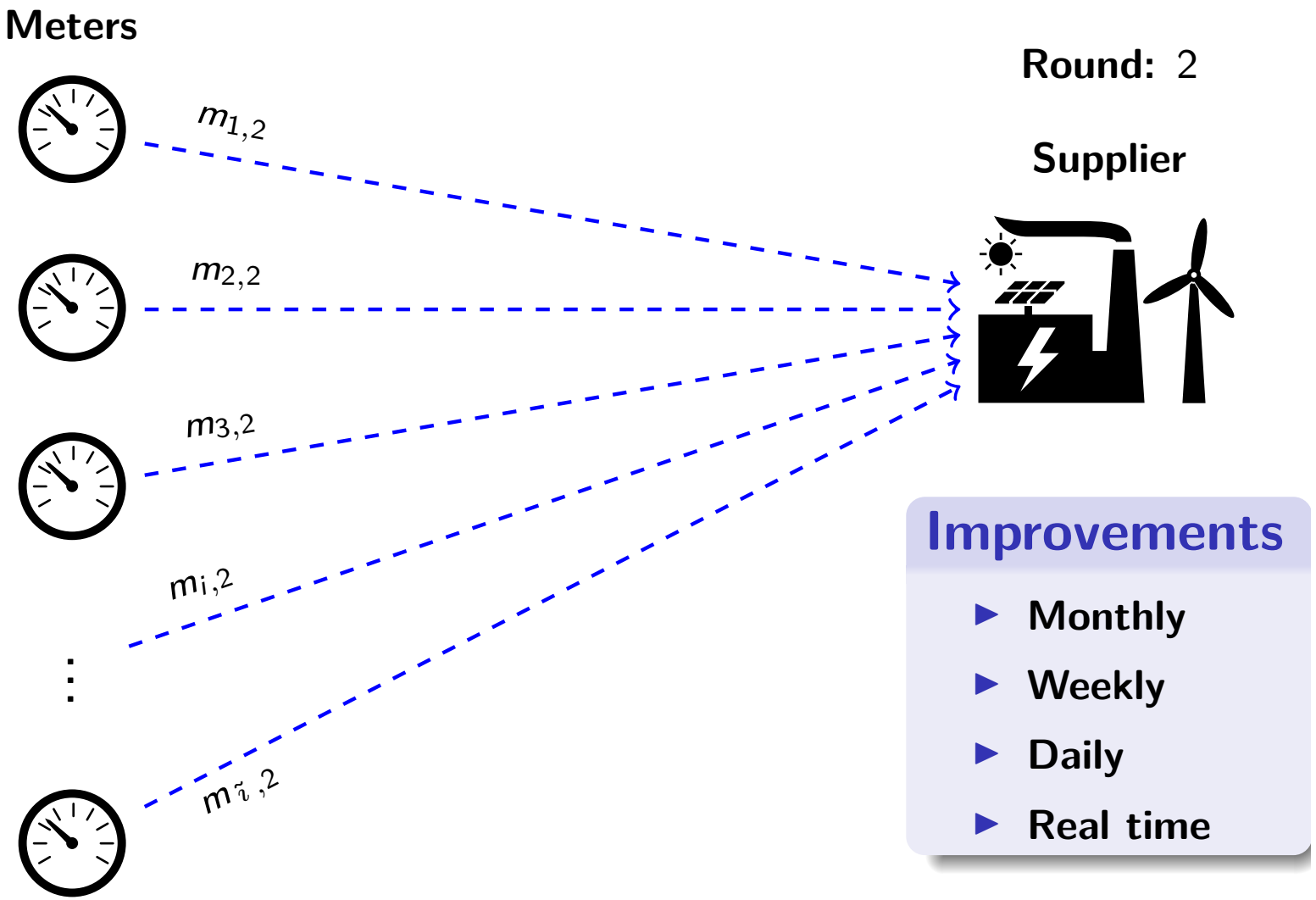


Improvements

- Monthly
- Weekly
- Daily
- Real time

Getting Smart

Collecting per round



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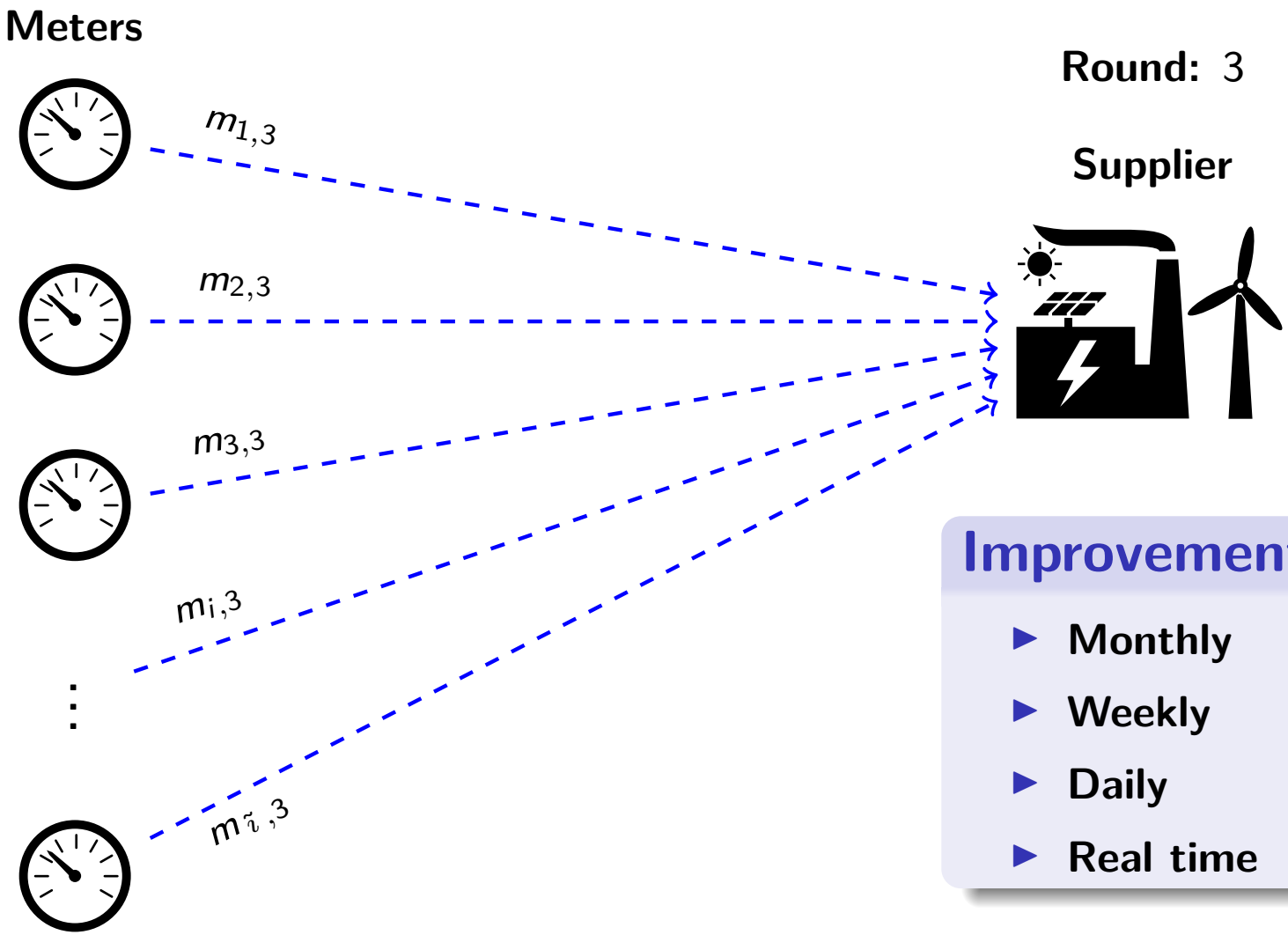

Improvements

- Monthly
- Weekly
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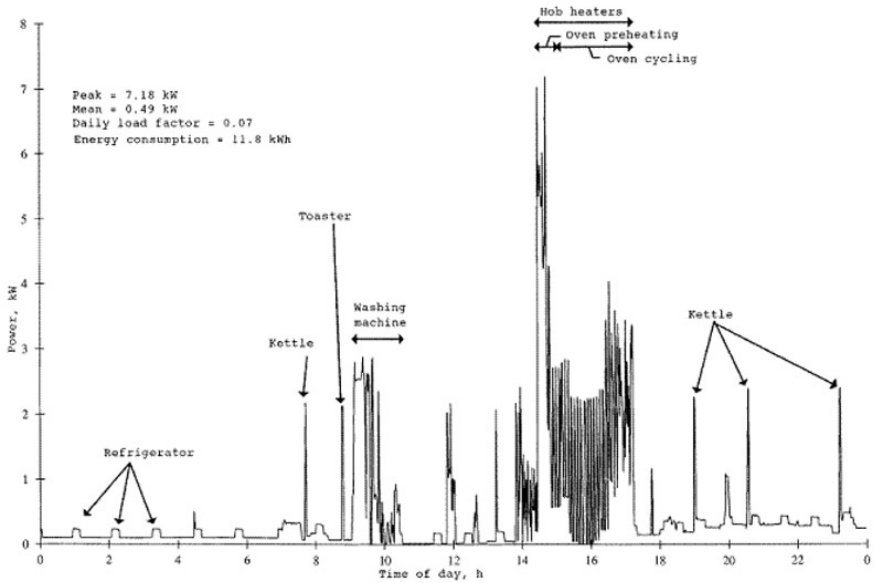
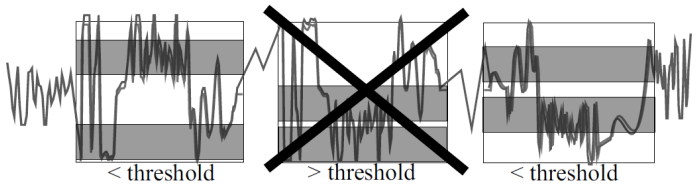
- Real time

Privacy Problem



[NIST]



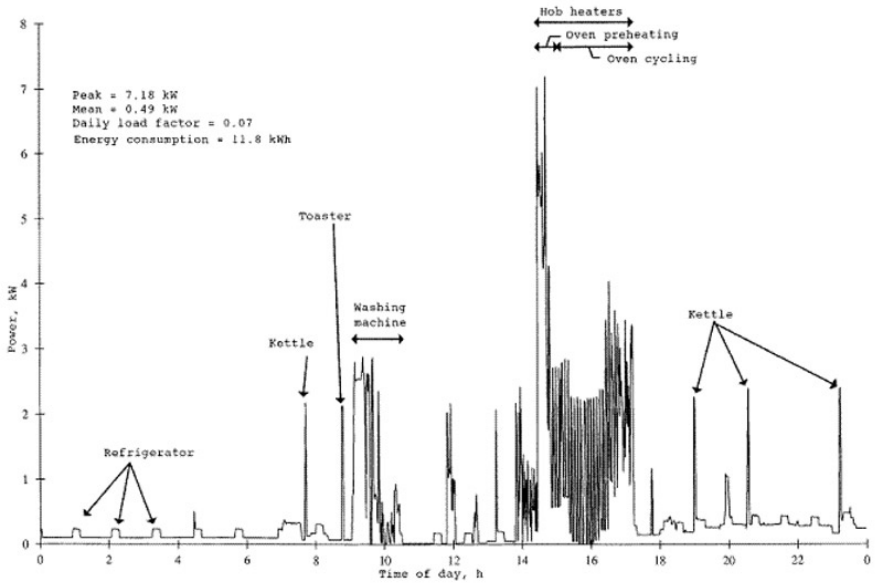
output matches to logfile

movie tng1
chunk 1 at 2103h

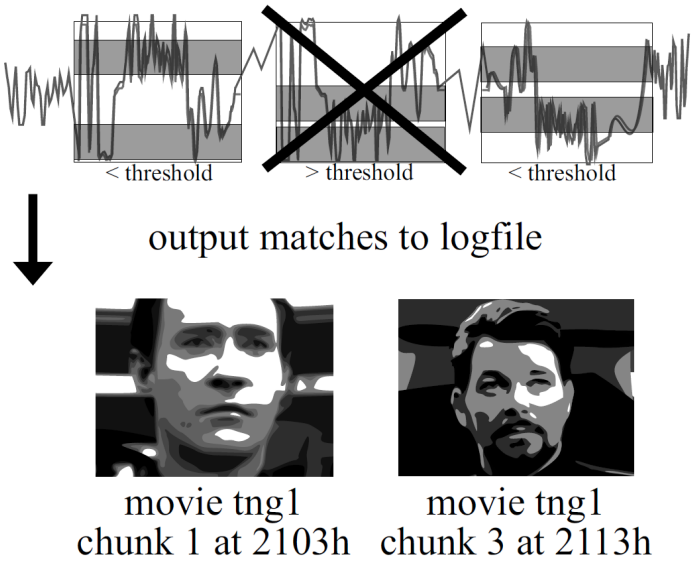
movie tng1
chunk 3 at 2113h

[GJL12]

Privacy Problem



[NIST]



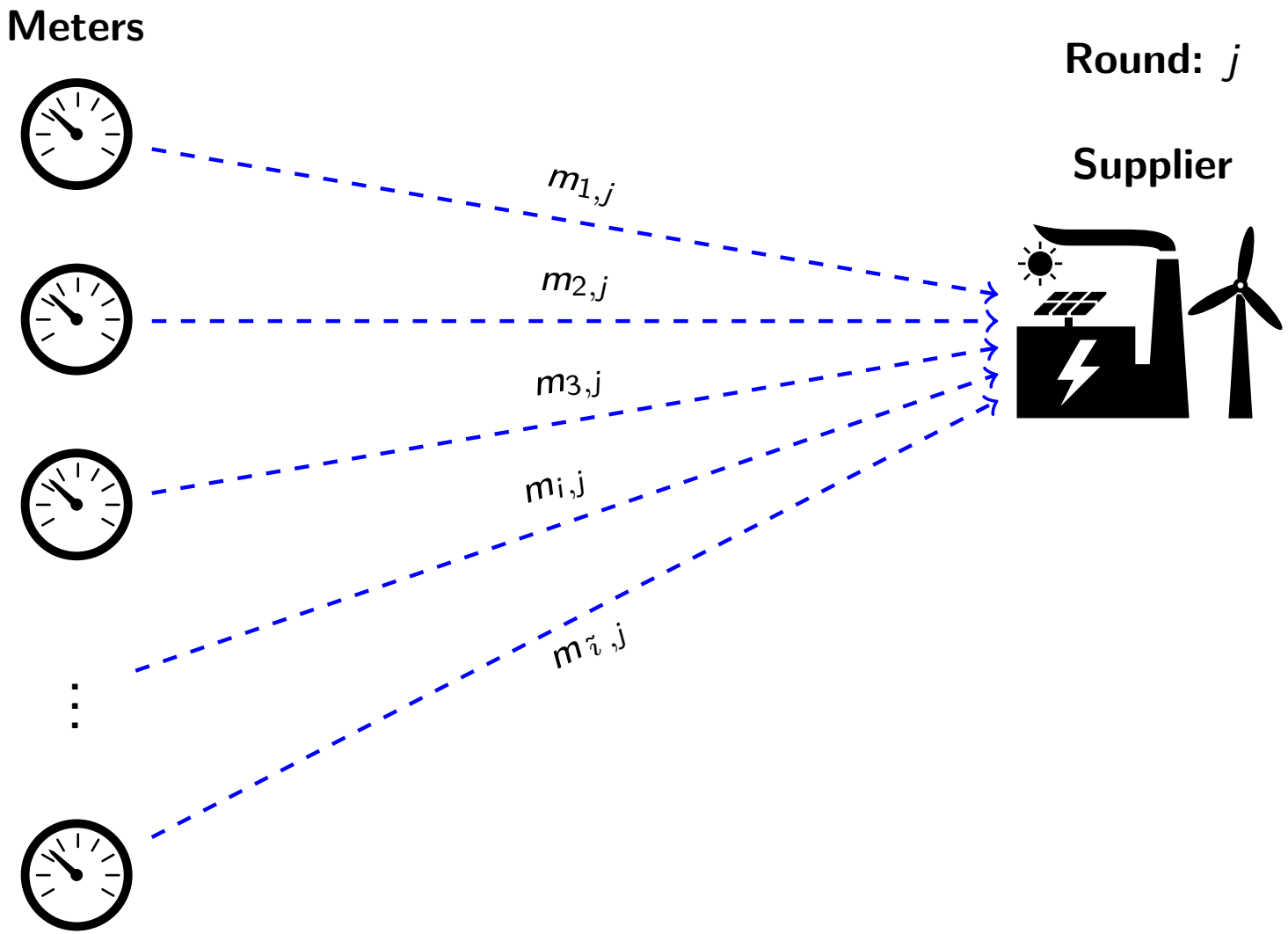
[GJL12]

EU - Official Journal L No.315

80% of households equipped with smart meters by 2020 in EU

Need for Encryption

Intercepting all measurements per round



Need for Encryption

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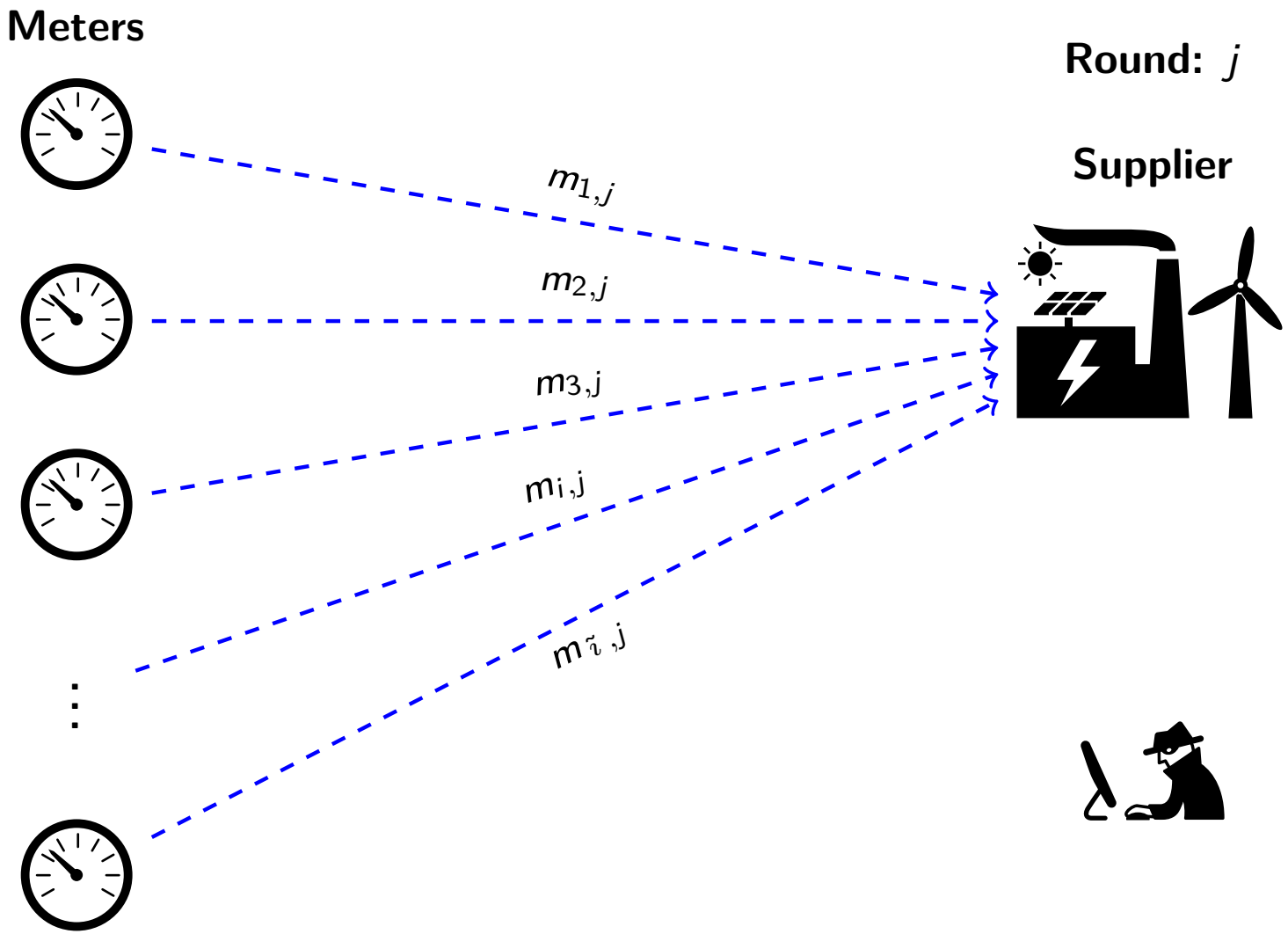

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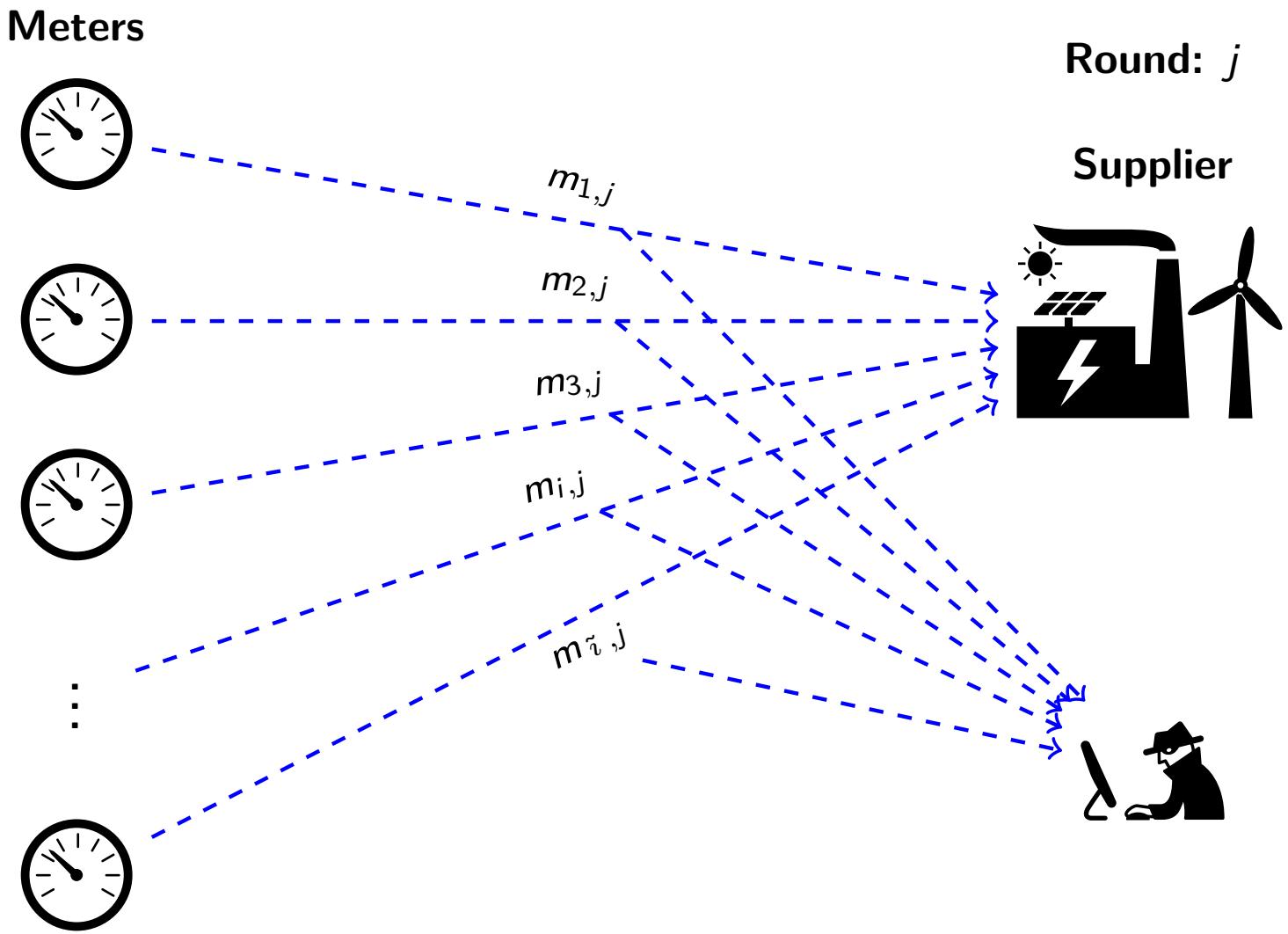
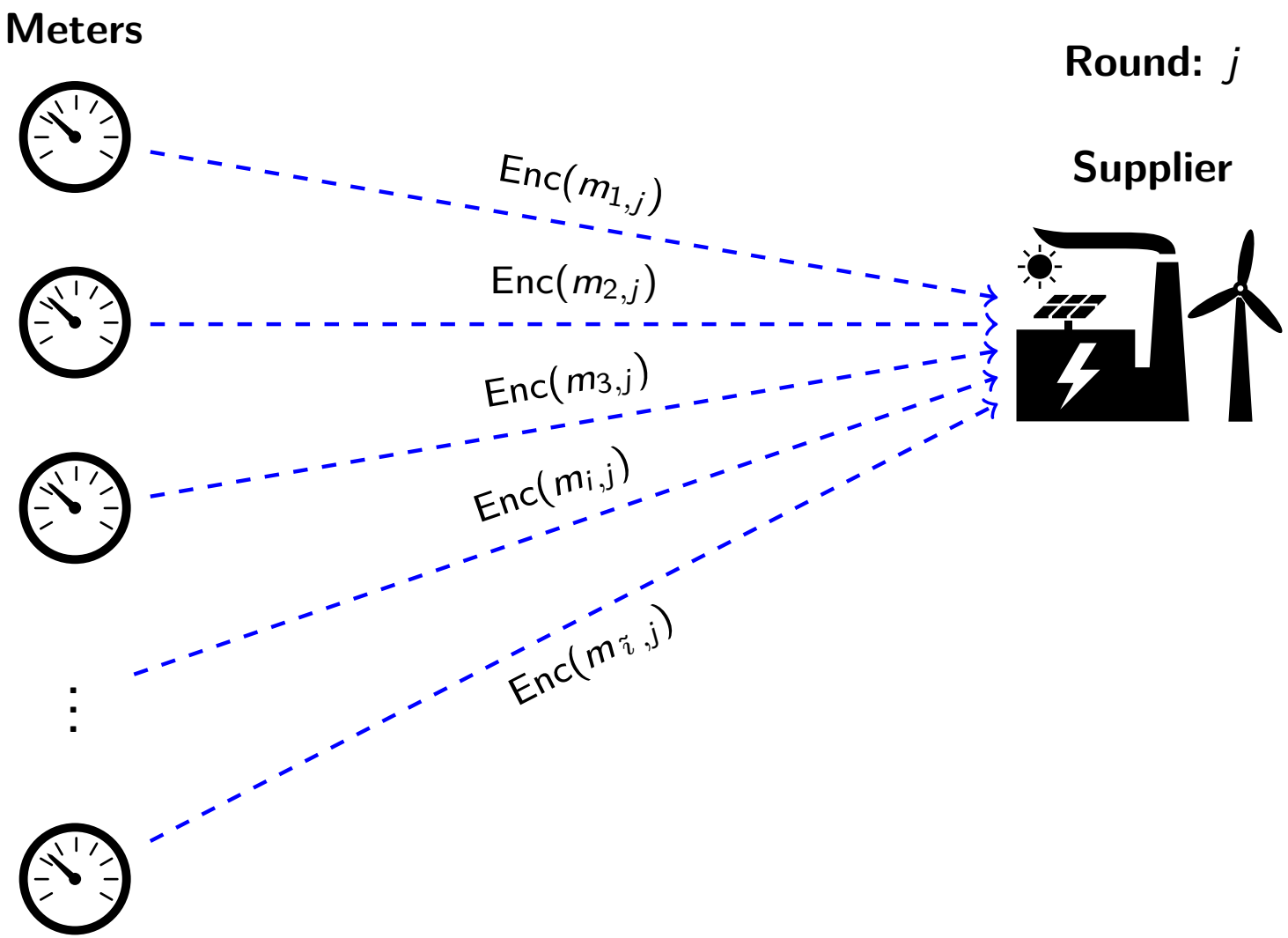
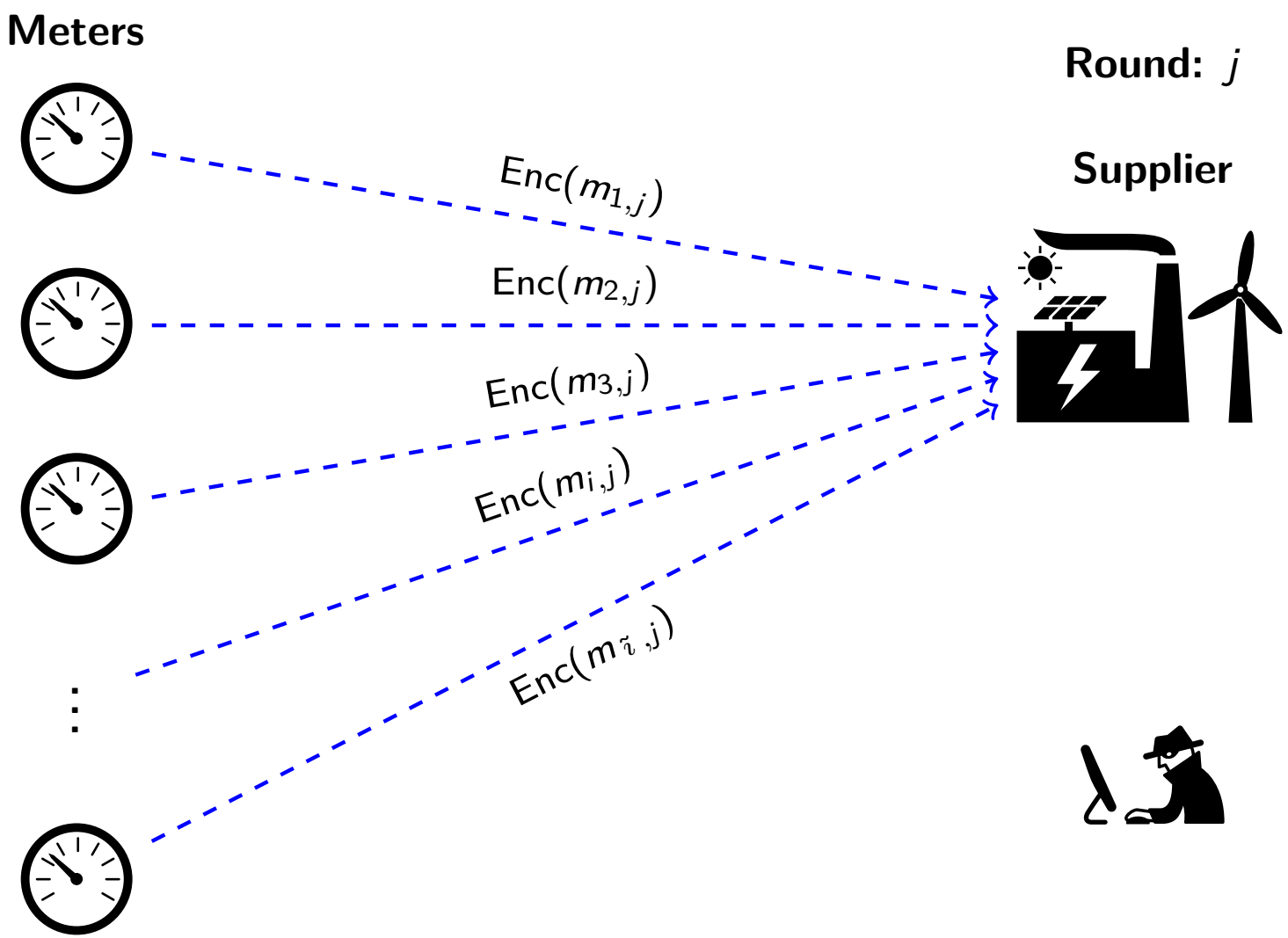


Need for Aggregation



Need for Aggregation



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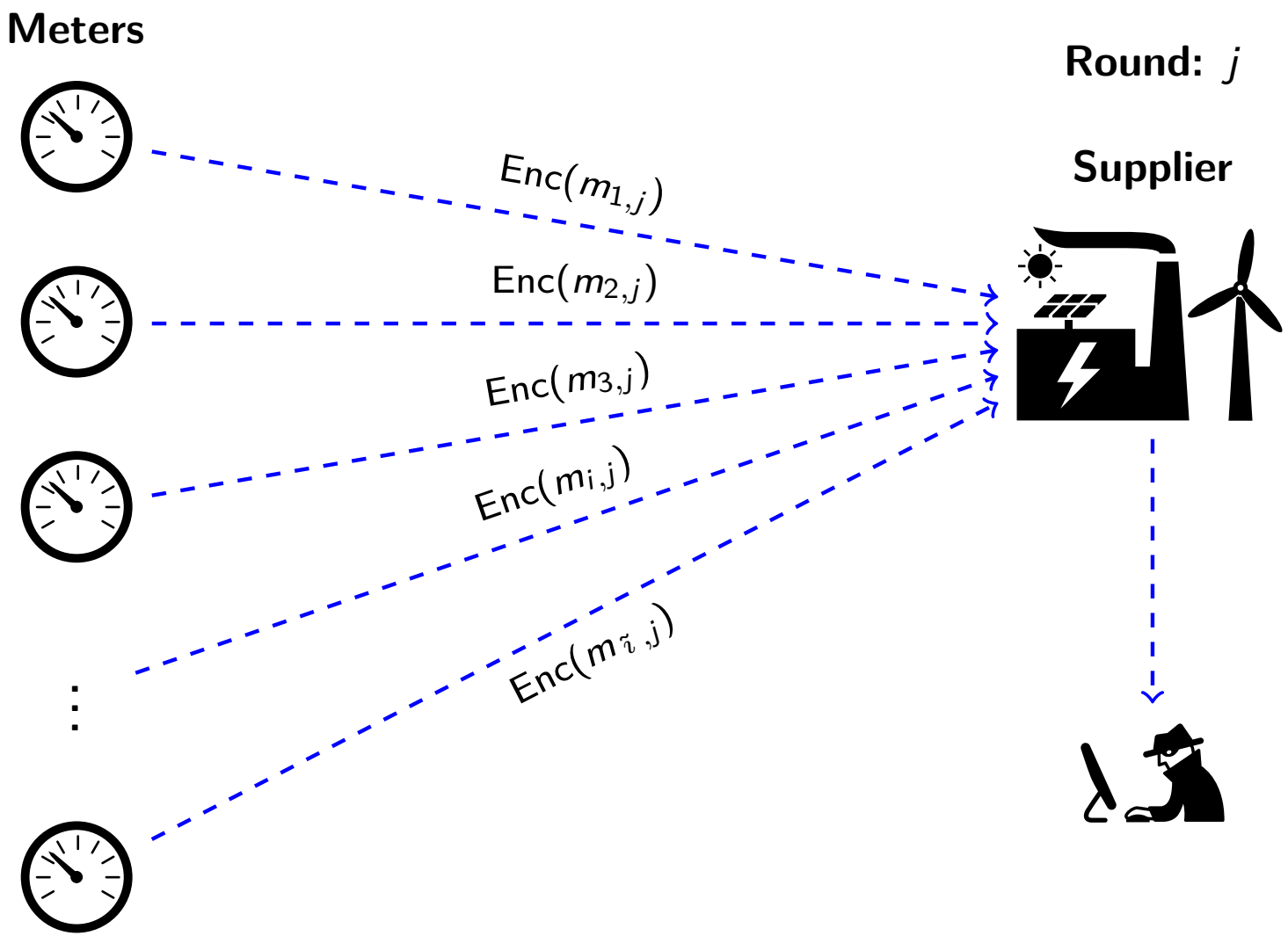


What Does the Supplier Need?

Consolidated Consumption versus Billing

Round	1	2	$\cdots$	$\tilde{j}$	**Billing**
Meter 1	$m_{1,1}$	$m_{1,2}$	$\cdots$	$m_{1,\tilde{j}}$	$\sum_{j=1}^{\tilde{j}} m_{1,j}$
Meter 2	$m_{2,1}$	$m_{2,2}$	$\cdots$	$m_{2,\tilde{j}}$	$\sum_{j=1}^{\tilde{j}} m_{2,j}$
$\vdots$	$\vdots$	$\vdots$	$\ddots$	$\vdots$	$\vdots$
Meter $\tilde{i}$	$m_{\tilde{i},1}$	$m_{\tilde{i},2}$	$\cdots$	$m_{\tilde{i},\tilde{j}}$	$\sum_{j=1}^{\tilde{j}} m_{\tilde{i},j}$
Consolidated	$\sum_{i=1}^{\tilde{i}} m_{i,1}$	$\sum_{i=1}^{\tilde{i}} m_{i,2}$	$\cdots$	$\sum_{i=1}^{\tilde{i}} m_{i,\tilde{j}}$	$=$

What Does the Supplier Need?

Consolidated Consumption versus Billing

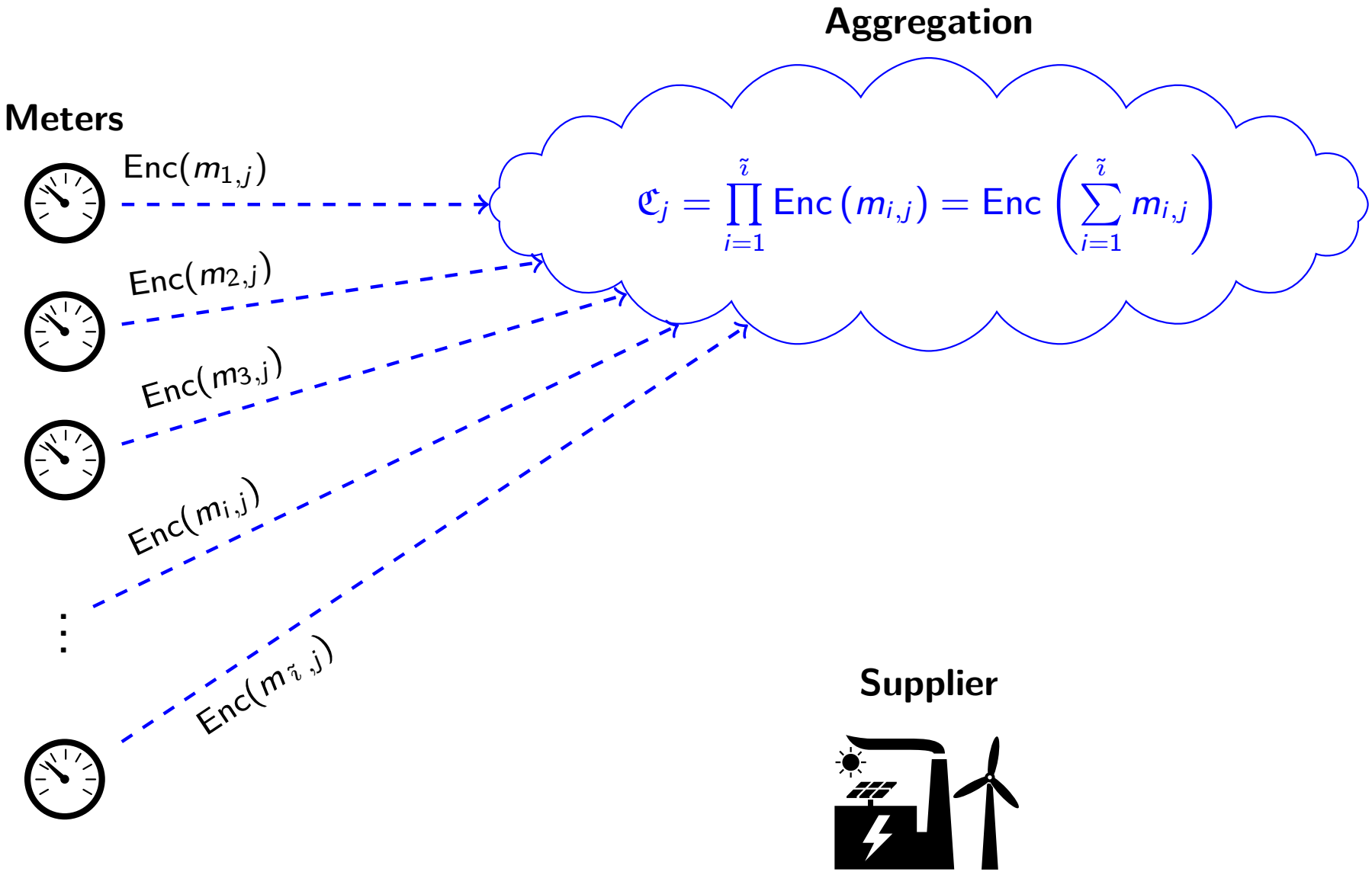
Round	1	2	$\cdots$	$\tilde{j}$	**Billing**
Meter 1	$m_{1,1}$	$m_{1,2}$	$\cdots$	$m_{1,\tilde{j}}$	$\sum_{j=1}^{\tilde{j}} m_{1,j}$
Meter 2	$m_{2,1}$	$m_{2,2}$	$\cdots$	$m_{2,\tilde{j}}$	$\sum_{j=1}^{\tilde{j}} m_{2,j}$
$\vdots$	$\vdots$	$\vdots$	$\ddots$	$\vdots$	$\vdots$
Meter $\tilde{i}$	$m_{\tilde{i},1}$	$m_{\tilde{i},2}$	$\cdots$	$m_{\tilde{i},\tilde{j}}$	$\sum_{j=1}^{\tilde{j}} m_{\tilde{i},j}$
Consolidated	$\sum_{i=1}^{\tilde{i}} m_{i,1}$	$\sum_{i=1}^{\tilde{i}} m_{i,2}$	$\cdots$	$\sum_{i=1}^{\tilde{i}} m_{i,\tilde{j}}$	$=$

✗ ✓

PPPs only work with large aggregations

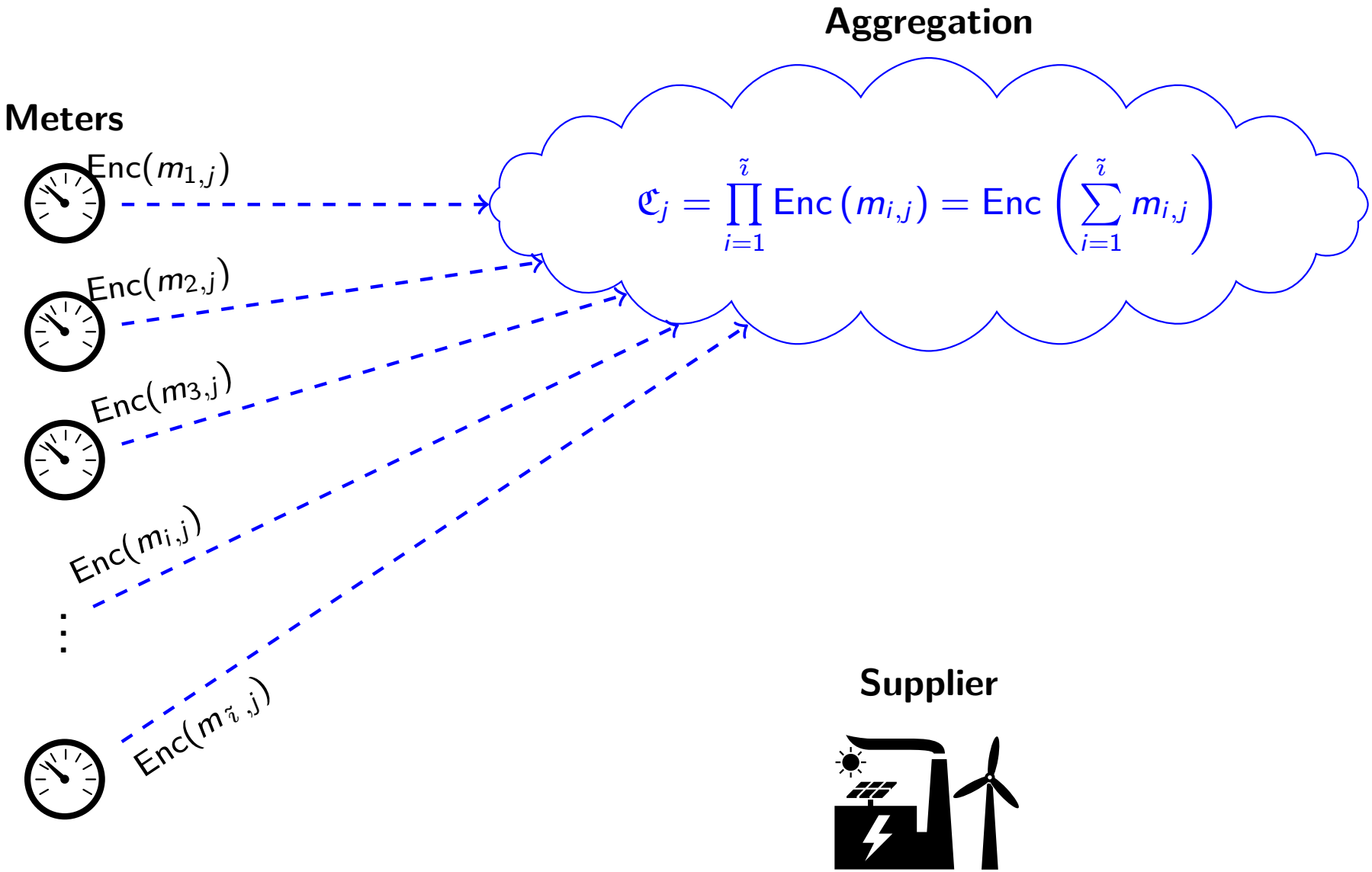
Aggregation

Additive homomorphic encryption primitives (AHEPs)



Aggregation

AHEPs



Aggregation

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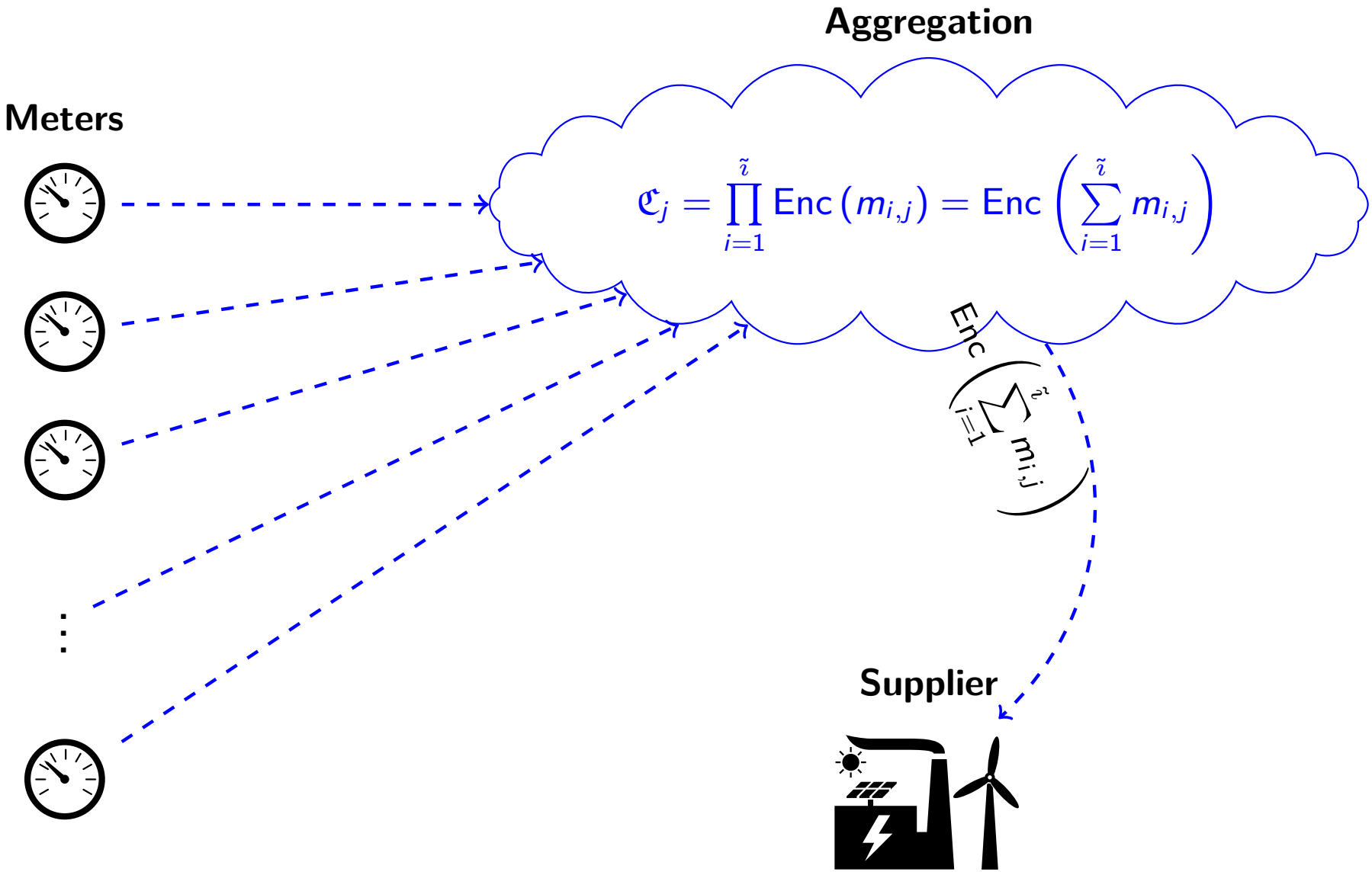

Requirement 1

Recoverability of consolidated consumption 

Requirements

Requirements for Smart Grids

Requirement 1

Recoverability of consolidated consumption 

Requirement 2

Recoverability of bill based on dynamic pricing 

Requirements

Requirements for Smart Grids

Requirement 1

Recoverability of consolidated consumption 

Requirement 2

Recoverability of bill based on dynamic pricing 

Requirement 3

Verification (auditability) 

Requirements

Requirements for Smart Grids

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Verification (auditability) 

Requirement 4

Efficiency 

CSR
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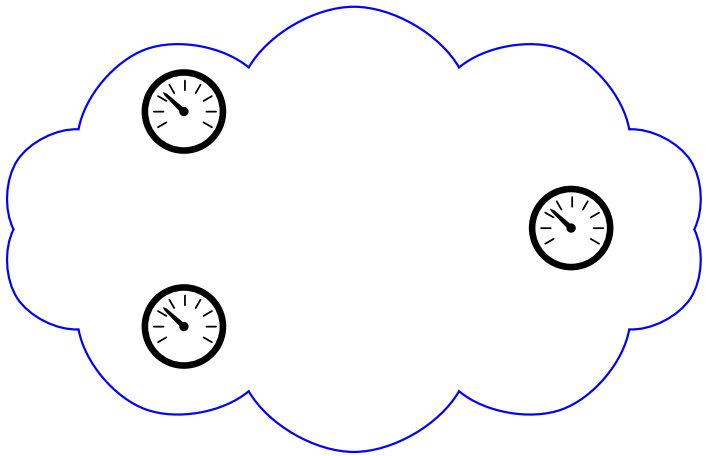
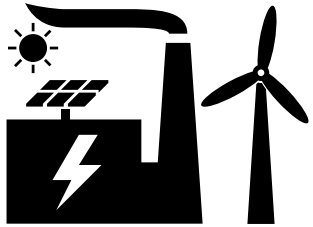
PPP1 - - SDC-Nets

SDC-Nets Using In-Network Aggregation [BM14a]

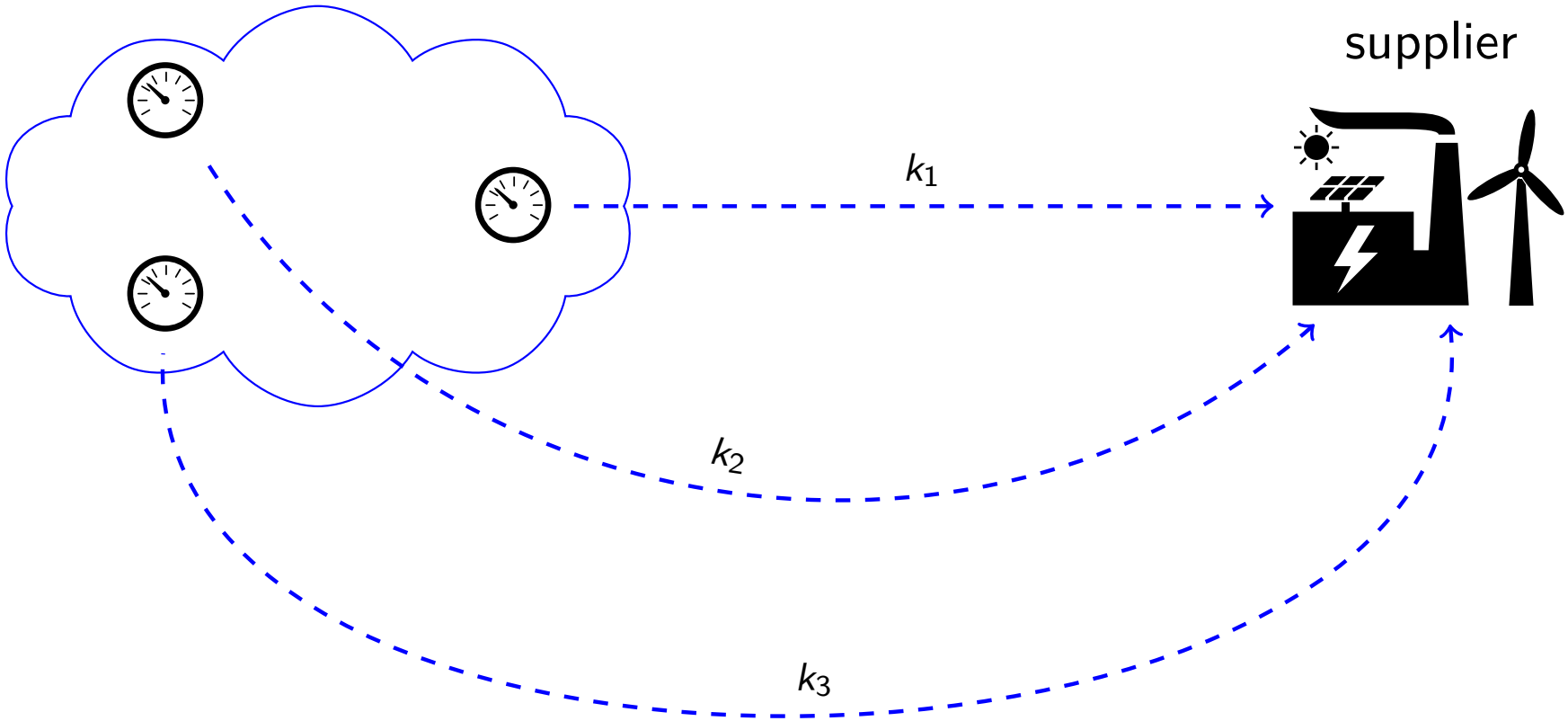


supplier



PPP1 - - SDC-Nets

SDC-Nets Using In-Network Aggregation [BM14a]



PPP1 -   - SDC-Nets

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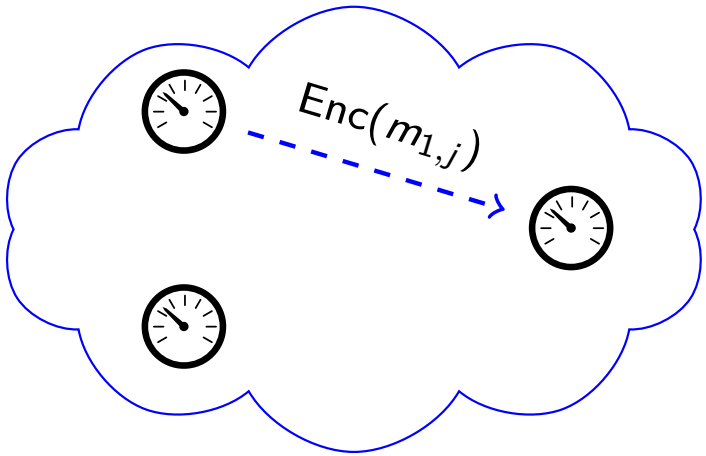
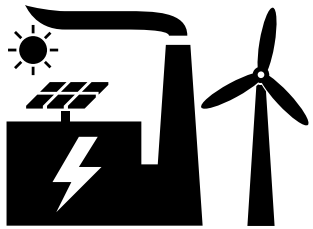


supplier



PPP1 - - SDC-Nets

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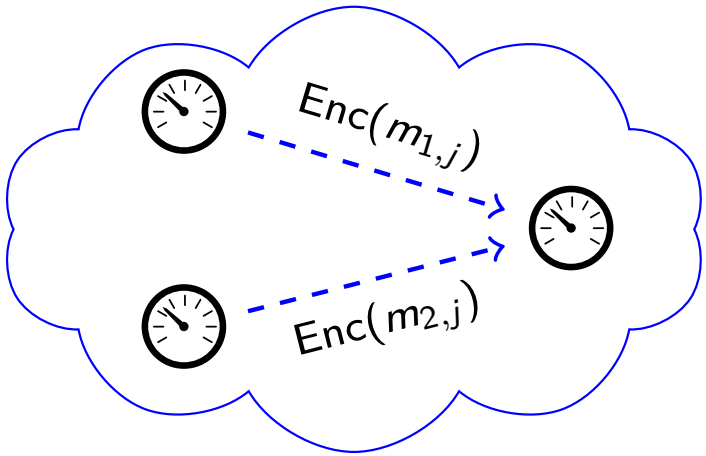
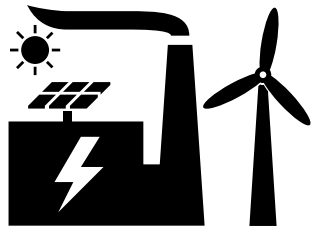
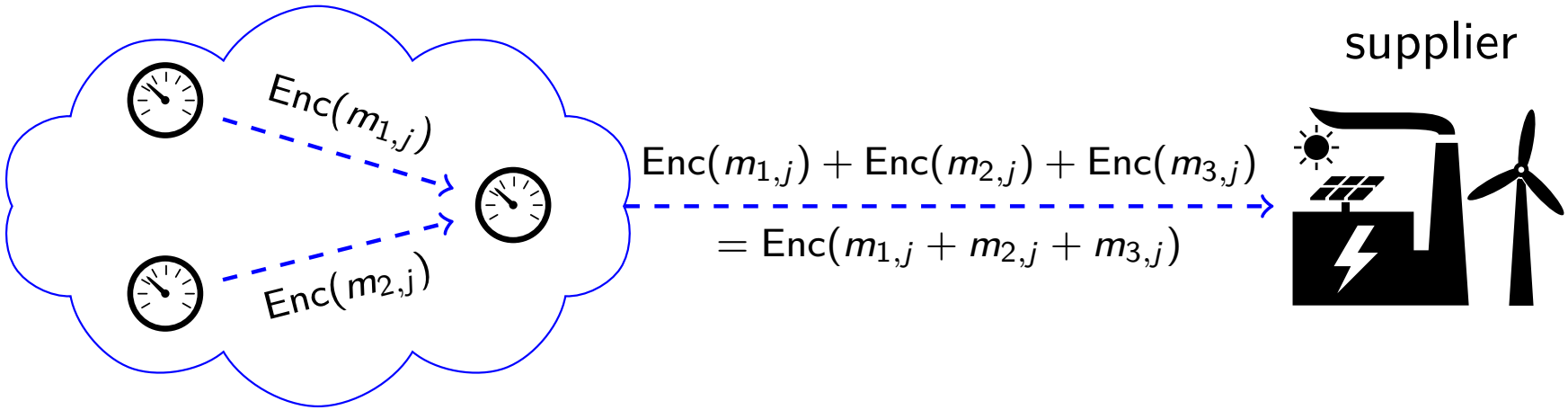


supplier



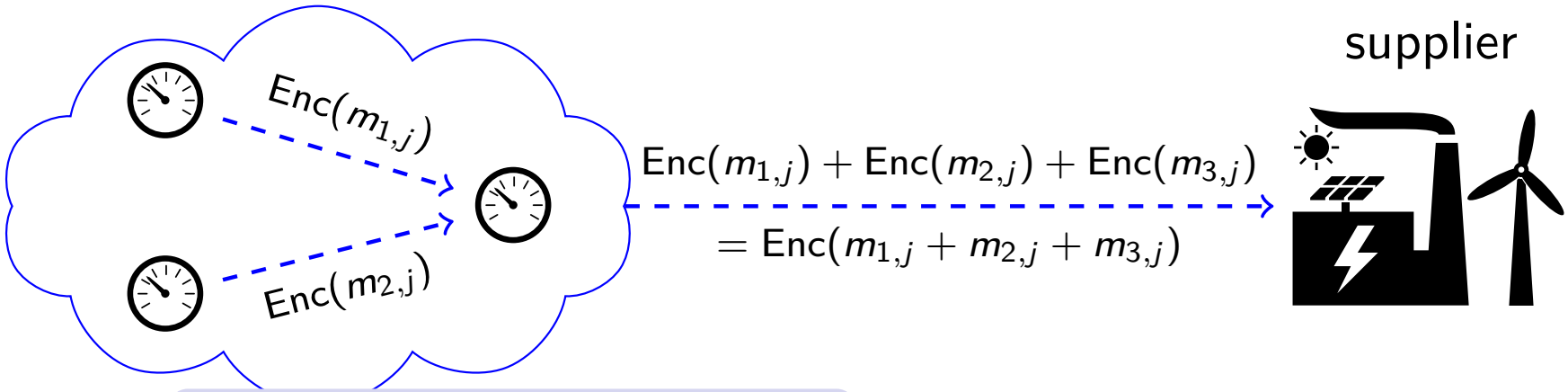
PPP1 - - SDC-Nets

SDC-Nets Using In-Network Aggregation [BM14a]



PPP1 - - SDC-Nets

SDC-Nets Using In-Network Aggregation [BM14a]

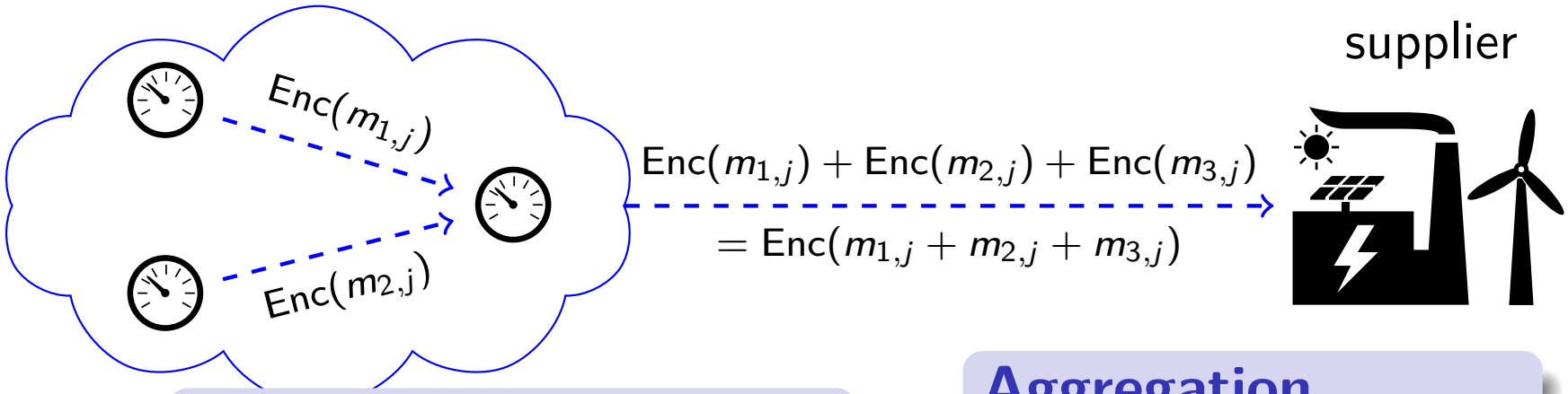


Encryption

$$\text{Enc}(m_{i,j}) = m_{i,j} + \text{H}(k_i||j)$$

PPP1 -  - SDC-Nets

SDC-Nets Using In-Network Aggregation [BM14a]



Encryption

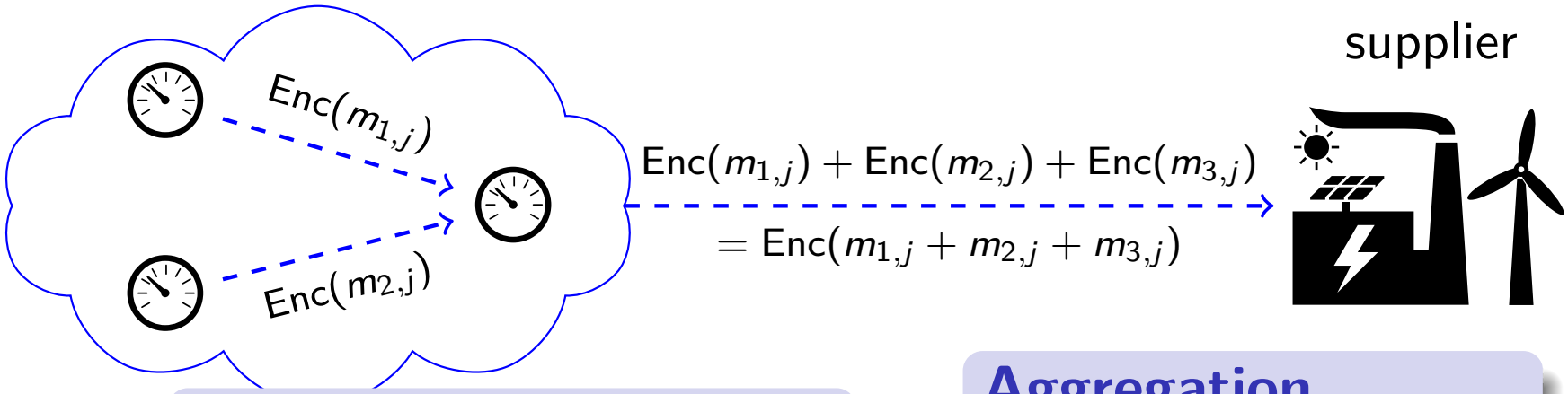
$$Enc(m_{i,j}) = m_{i,j} + H(k_i||j)$$

Aggregation

$$C = \sum_{i=1}^{N} Enc\,(m_{i,j})$$

PPP1 - - SDC-Nets

SDC-Nets Using In-Network Aggregation [BM14a]



Encryption

$$\mathrm{Enc}(m_{i,j}) = m_{i,j} + \mathrm{H}(k_i||j)$$

Aggregation

$$C = \sum_{i=1}^{N} \mathrm{Enc}\,(m_{i,j})$$

Decryption

$$\mathrm{Dec}\,(C) = C - \sum_{i=1}^{N} \mathrm{H}(k_i||j) = \sum_{i=1}^{N} m_{i,j}$$

PPP1

PPP1 meets the following requirements

Requirement 1 - ✓

Recoverability of consolidated consumption 

Requirement 2 - ✗

Recoverability of bill based on dynamic pricing 

Requirement 3 - ✗

Verification (auditability) 

Requirement 4 - ✓

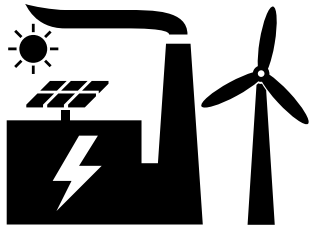
Efficiency 

PPP2 - - Commitment

Commitment Based on ECC [BM14a]

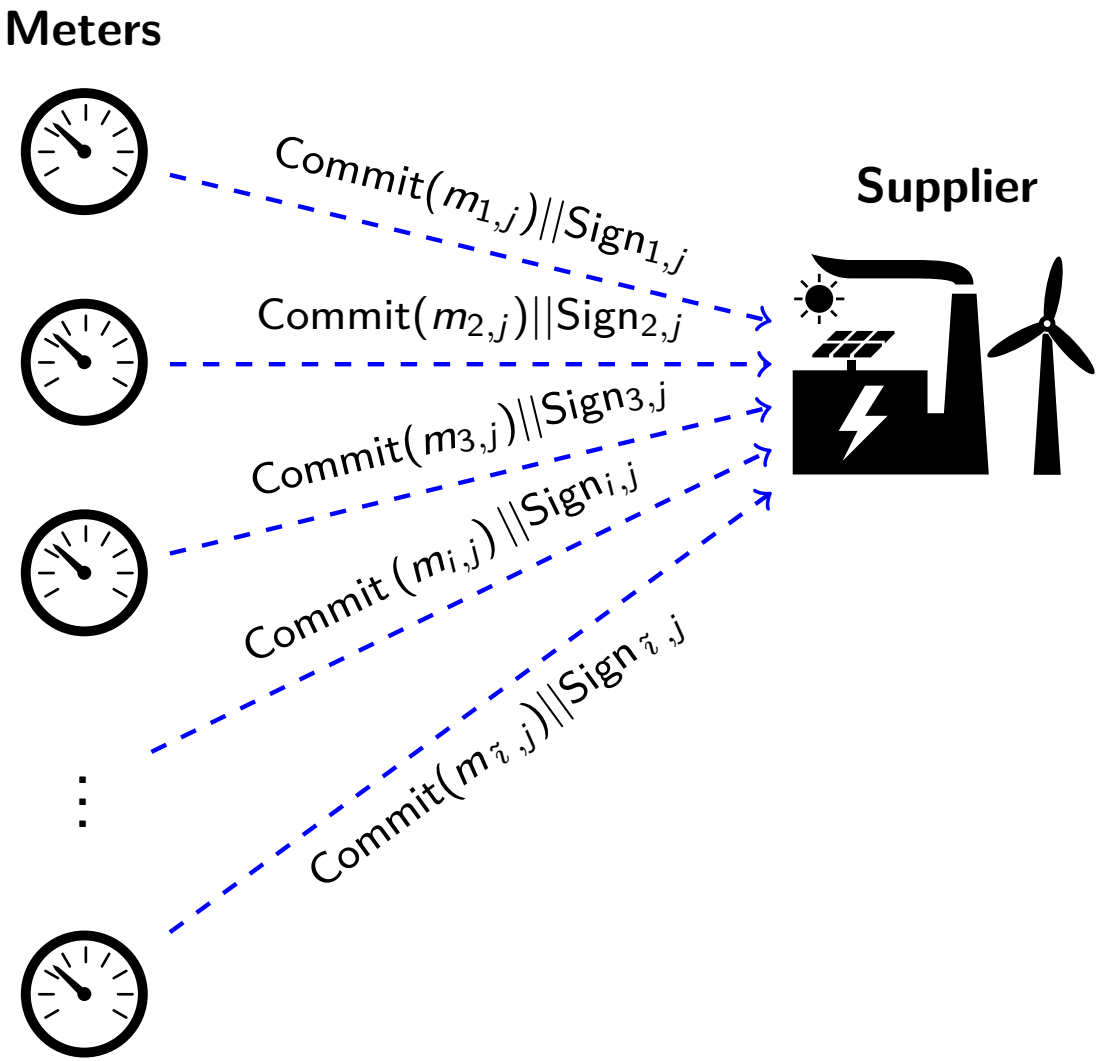
Meters

Supplier



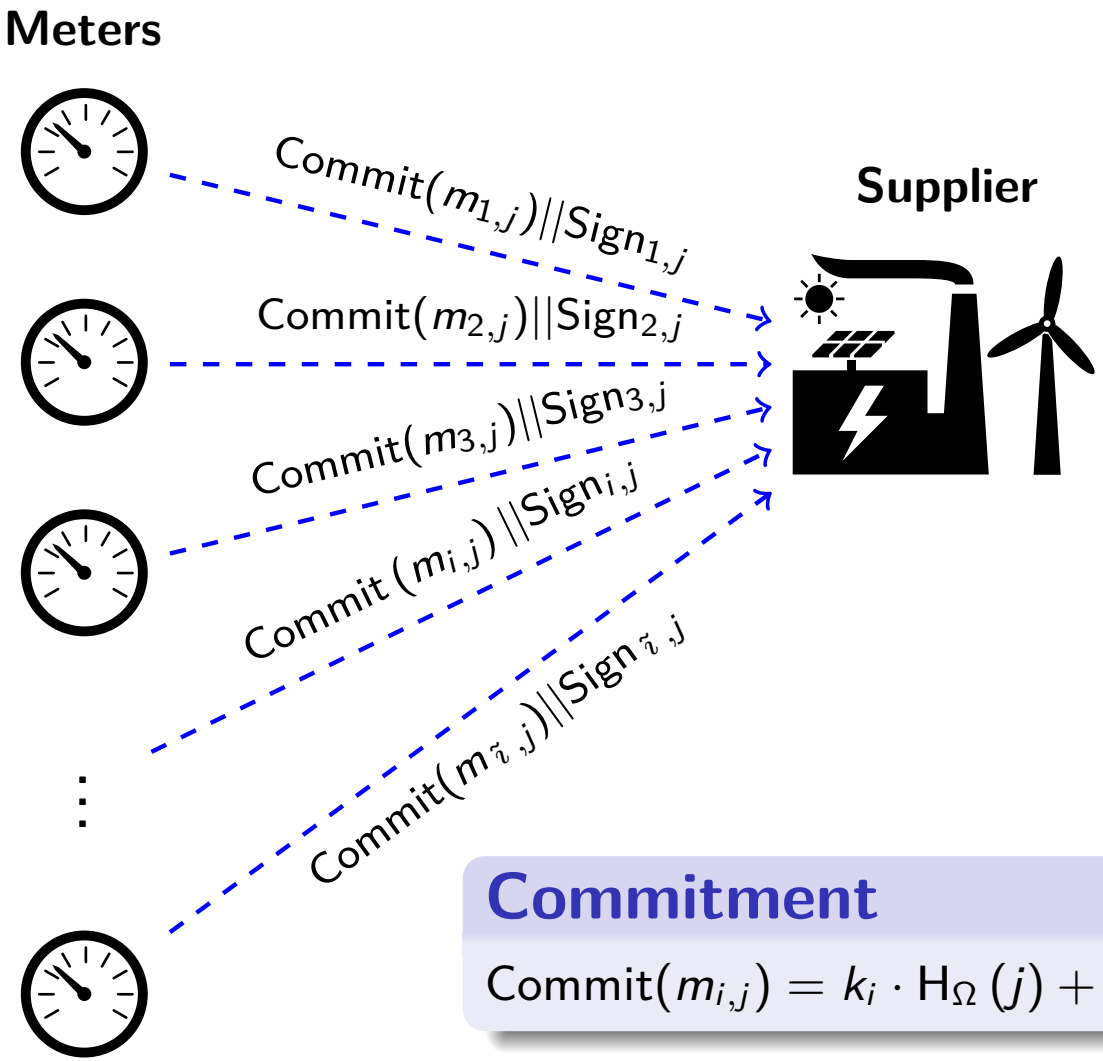
PPP2 -  - Commitment

Commitment Based on ECC [BM14a]



PPP2 -  - Commitment

Commitment Based on ECC [BM14a]



Commitment

$$\text{Commit}(m_{i,j}) = k_i \cdot \text{H}_\Omega(j) + m_{i,j} \cdot P$$

PPP2

PPP2 meets the following requirements

Requirement 1 - ✗

Recoverability of consolidated consumption 

Requirement 2 - ✓

Recoverability of bill based on dynamic pricing 

Requirement 3 - ✓

Verification (auditability) 

Requirement 4 - ✓

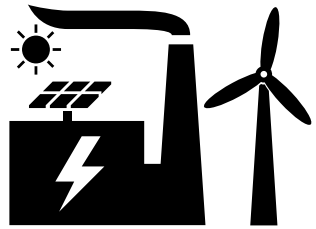
Efficiency 

PPP2 - Verification

[BDBBM14; BM14b; BM14a; BBM14; BVM15]

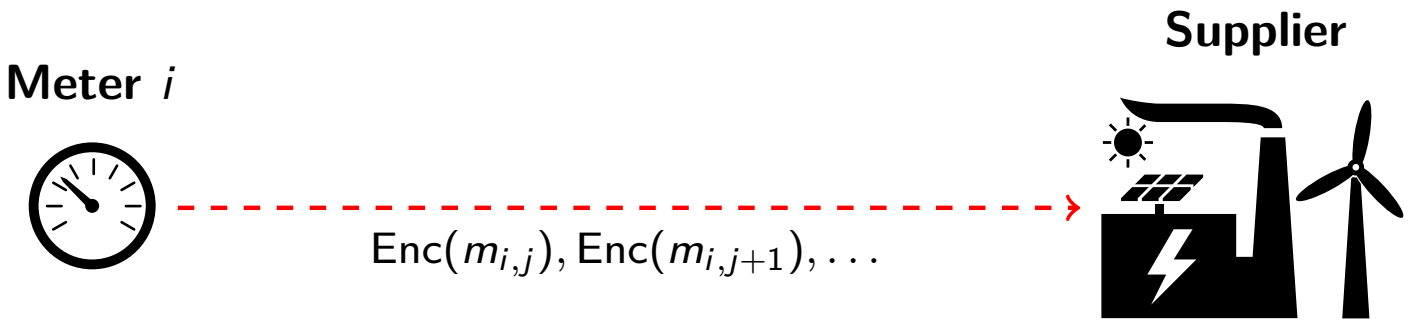
Meter *i*

Supplier



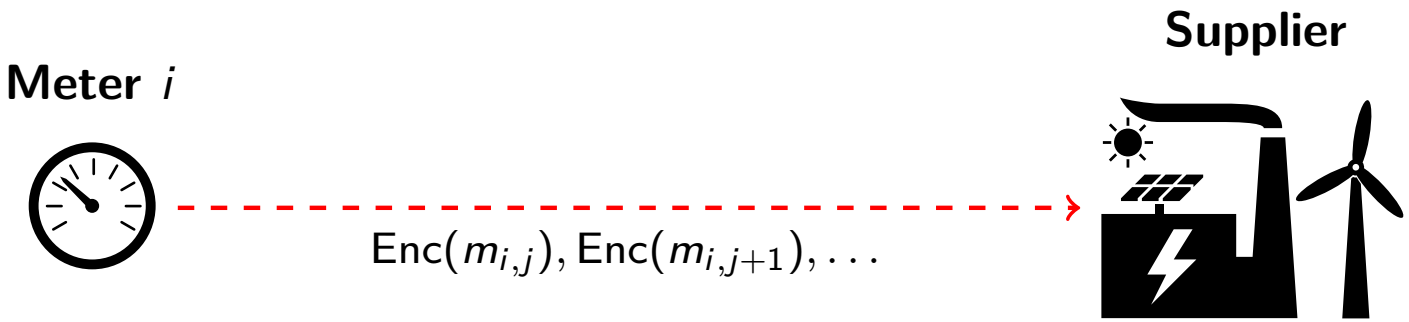
PPP2 - Verification

[BDBBM14; BM14b; BM14a; BBM14; BVM15]



PPP2 - Verification

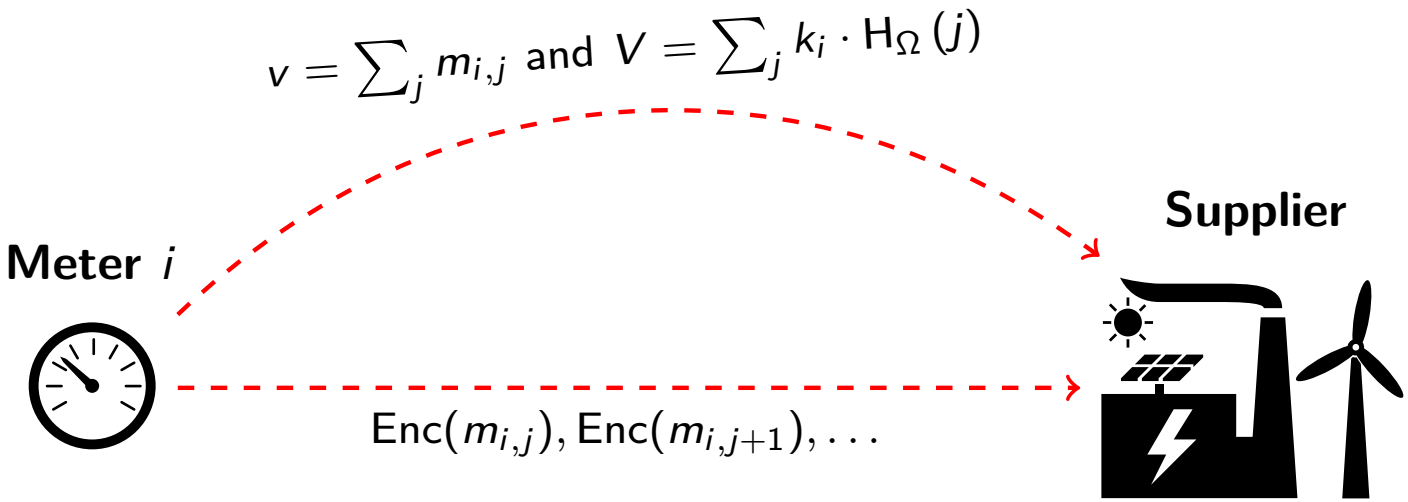
[BDBBM14; BM14b; BM14a; BBM14; BVM15]



$$Q = \sum_j \mathsf{Enc}(m_{i,j}) = \sum_j k_i \cdot \mathrm{H}_\Omega(j) + m_{i,j} \cdot P$$

PPP2 - Verification

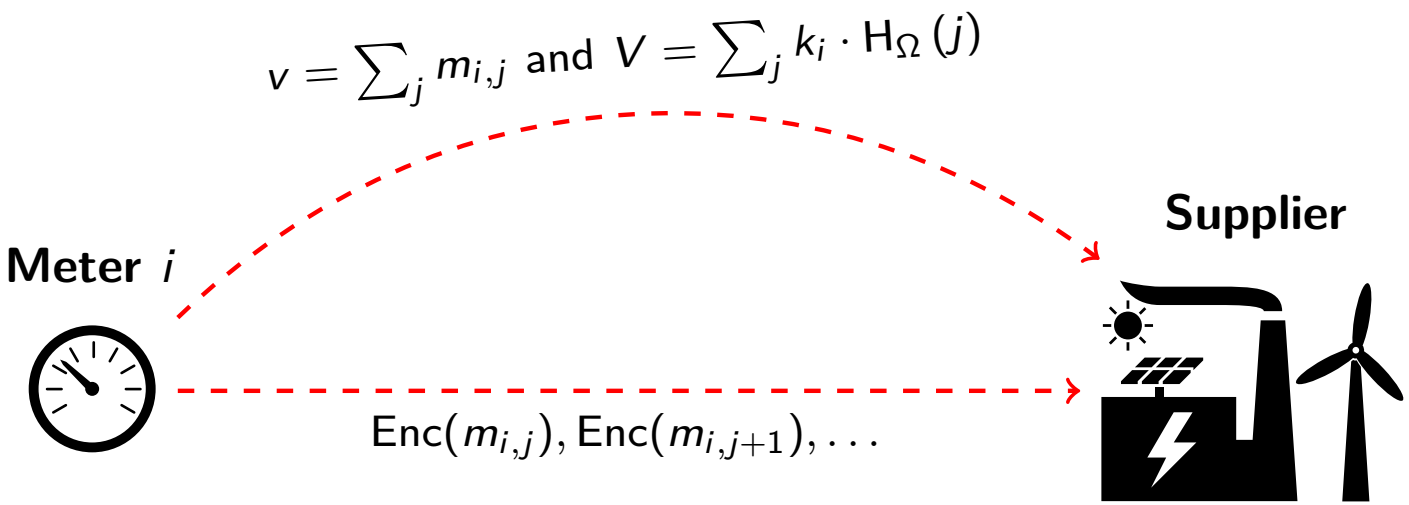
[BDBBM14; BM14b; BM14a; BBM14; BVM15]



$$Q = \sum_j \mathrm{Enc}(m_{i,j}) = \sum_j k_i \cdot \mathrm{H}_\Omega(j) + m_{i,j} \cdot P$$

PPP2 - Verification

[BDBBM14; BM14b; BM14a; BBM14; BVM15]



$$Q = \sum_j \mathrm{Enc}(m_{i,j}) = \sum_j k_i \cdot \mathrm{H}_\Omega(j) + m_{i,j} \cdot P$$

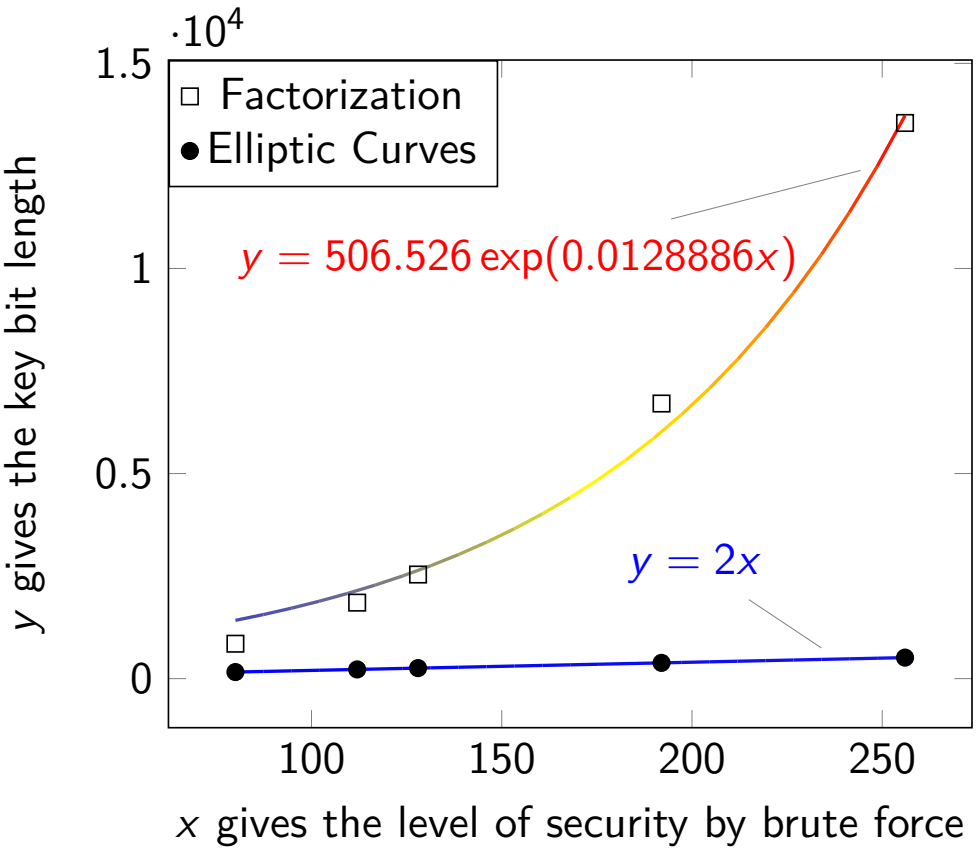
Verification

$$v \cdot P \stackrel{?}{=} Q - V$$

PPP2 - Performance

[BM14b; BM14a; BVM15; BDBBM14; LBPN12]

$$\exp\left(\left(\left(\frac{64}{9}\right)^{1/3} + O(1)\right)(\ln n)^{1/3}(\ln\ln n)^{2/3}\right) = 2^x = \sqrt{\frac{\pi o}{2}},$$



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- PPP4 - Based on Quantum Cryptography

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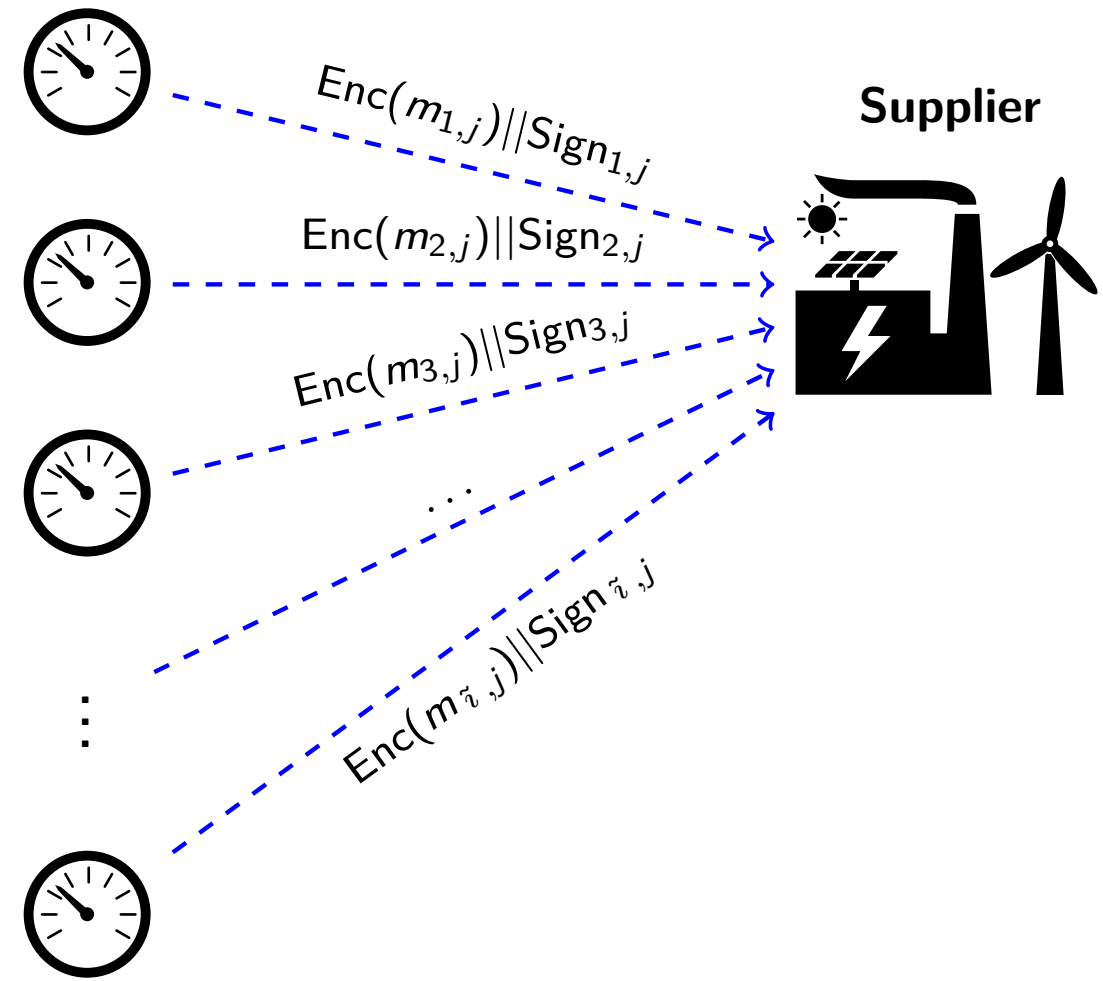
PPP3 -  - New Concept

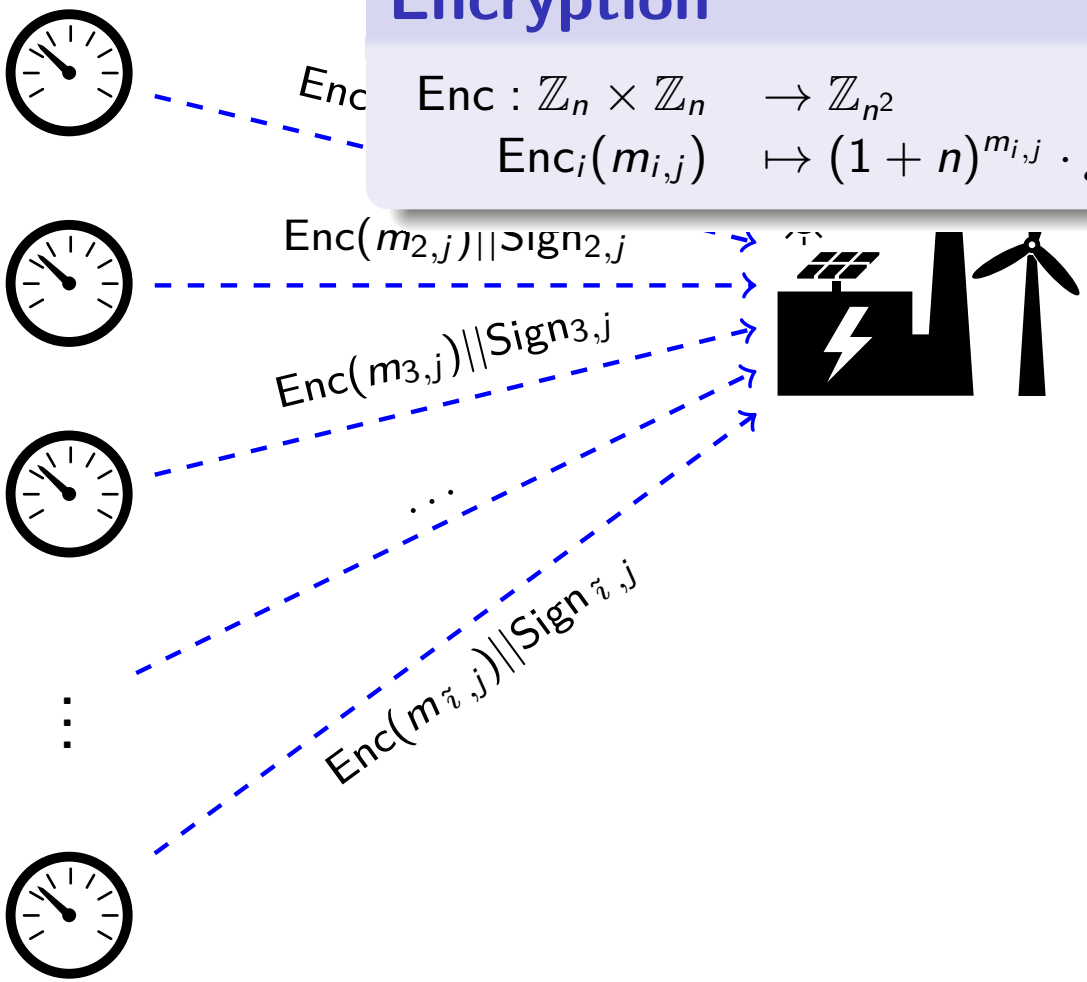
ADC-Net - [BBM14; BM14b; BVM15]



PPP3 -  - New Concept

ADC-Net - [BBM14; BM14b; BVM15]

Meters

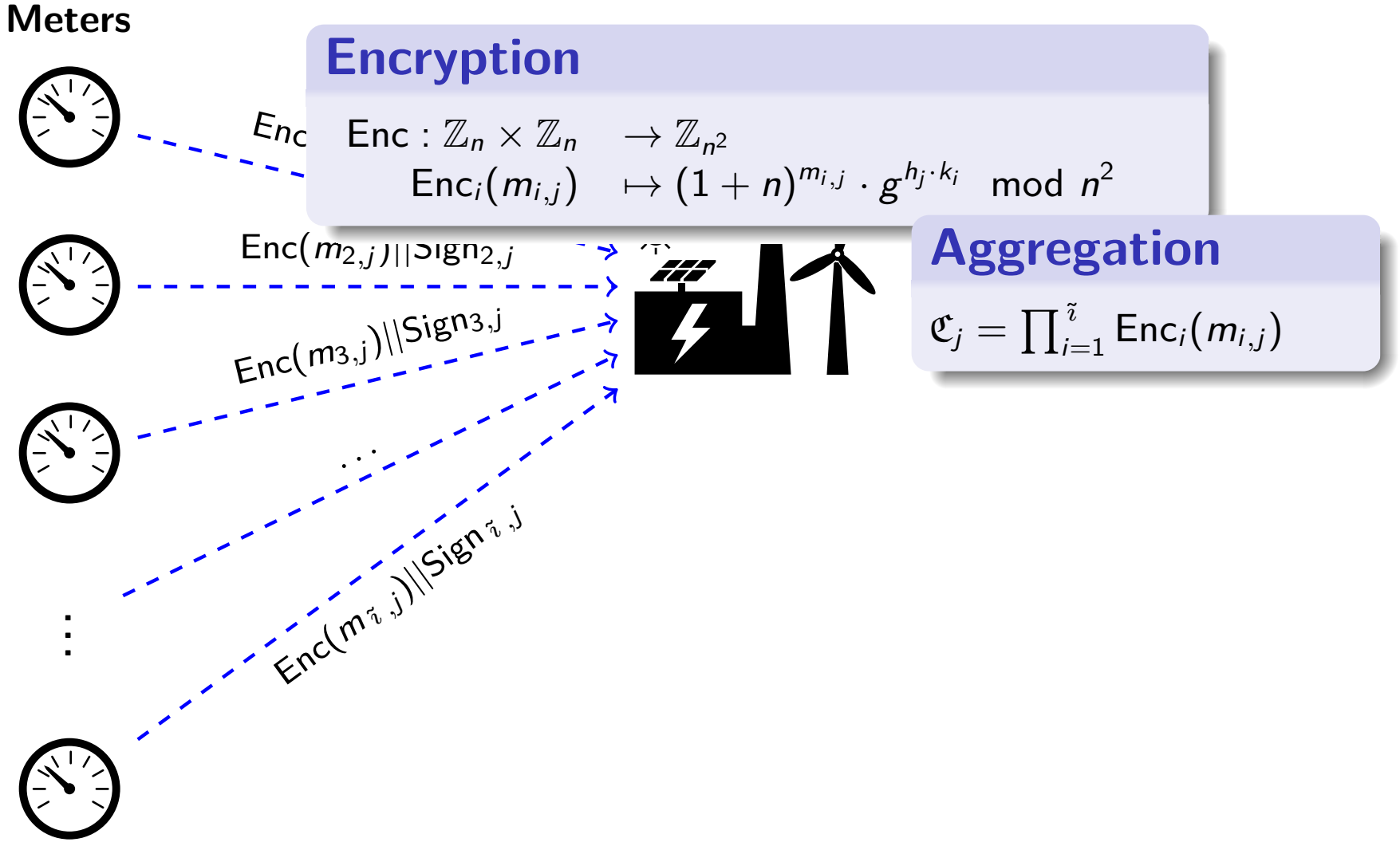


Encryption

$$\begin{aligned} \mathrm{Enc} : \mathbb{Z}_n \times \mathbb{Z}_n &\to \mathbb{Z}_{n^2} \\ \mathrm{Enc}_i(m_{i,j}) &\mapsto (1+n)^{m_{i,j}} \cdot g^{h_j \cdot k_i} \mod n^2 \end{aligned}$$

PPP3 -  - New Concept

ADC-Net - [BBM14; BM14b; BVM15]



PPP3 -  - New Concept

ADC-Net - [BBM14; BM14b; BVM15]

Meters




$\mathrm{Enc}(m_{2,j})||\mathrm{Sign}_{2,j}$

$\mathrm{Enc}(m_{3,j})||\mathrm{Sign}_{3,j}$

$\vdots$

$\mathrm{Enc}(m_{\tilde{i},j})||$

Encryption

$$\begin{aligned} \mathrm{Enc} : \mathbb{Z}_n \times \mathbb{Z}_n &\to \mathbb{Z}_{n^2} \\ \mathrm{Enc}_i(m_{i,j}) &\mapsto (1+n)^{m_{i,j}} \cdot g^{h_j \cdot k_i} \mod n^2 \end{aligned}$$

Aggregation

$$\mathfrak{C}_j = \prod_{i=1}^{\tilde{i}} \mathrm{Enc}_i(m_{i,j})$$

Decryption

$$\begin{aligned} \mathrm{Dec} : \mathbb{Z}_{n^2} &\to \mathbb{Z}_n \\ \mathrm{Dec}\,(\mathfrak{C}_j) &\mapsto \frac{\left(\mathfrak{C}_j \cdot g^{-h_t \cdot s} \mod n^2\right) - 1}{n} \end{aligned}$$

PPP3

PPP3 meets the following requirements

Requirement 1 - ✓

Recoverability of consolidated consumption 

Requirement 2 - ✓

Recoverability of bill based on dynamic pricing 

Requirement 3 - ✓

Verification (auditability) 

Requirement 4 - ✓

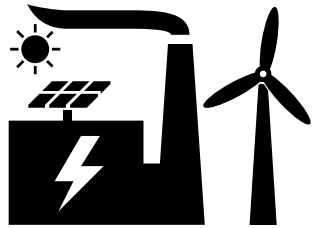
Efficiency 

PPP4 -  - Quantum Cryptography

No Keys [BSM14; BPP12]

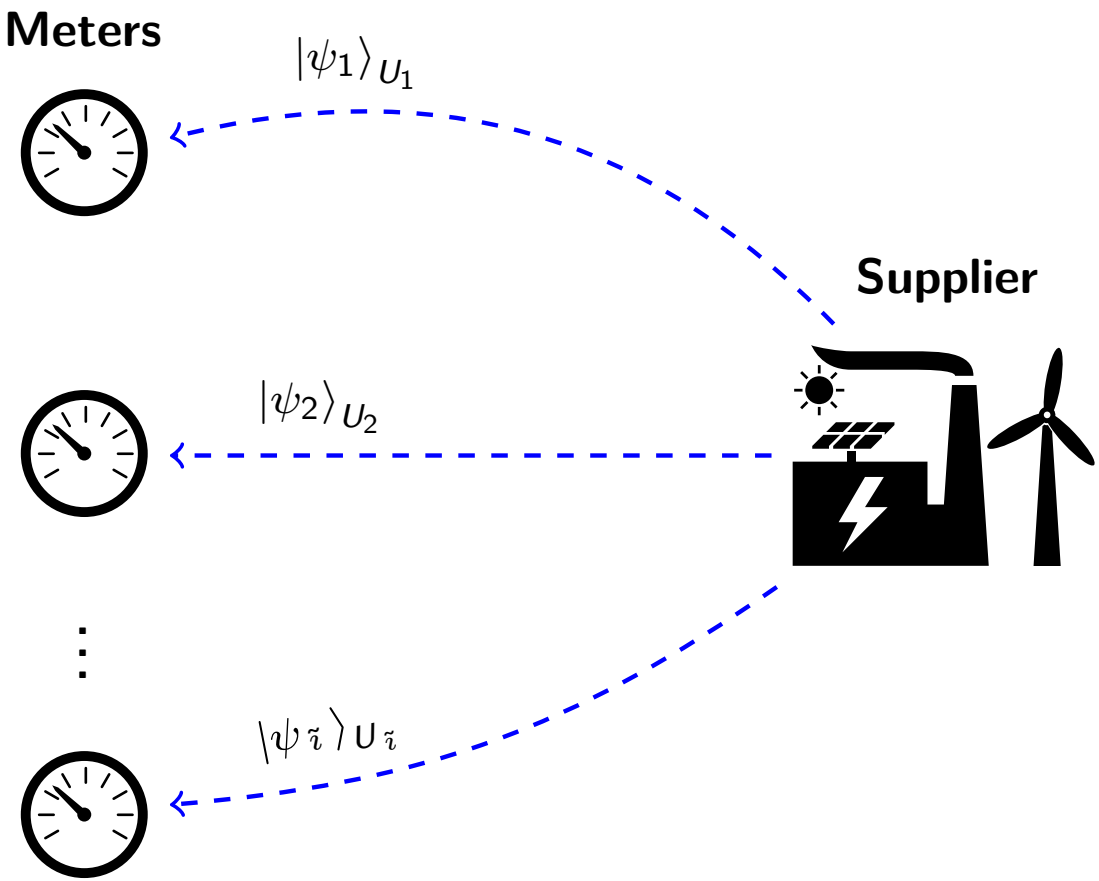
Meters

Supplier



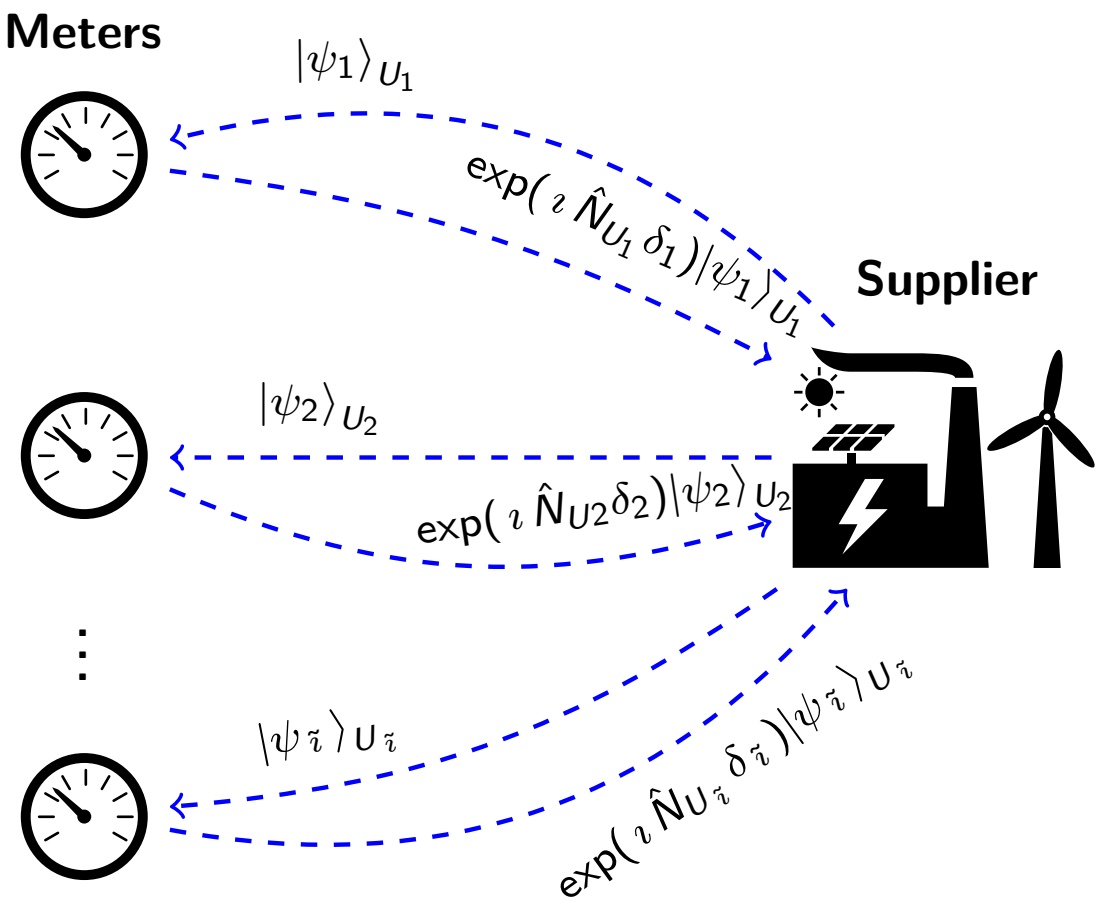
PPP4 -  - Quantum Cryptography

No Keys [BSM14; BPP12]



PPP4 - - Quantum Cryptography

No Keys [BSM14; BPP12]



PPP4

PPP4 meets the following requirements

Requirement 1 - ✓

Recoverability of consolidated consumption 

Requirement 2 - ✗

Recoverability of bill based on dynamic pricing 

Requirement 3 - ✗

Verification (auditability) 

Requirement 4 - depends on quantum devices

Efficiency 

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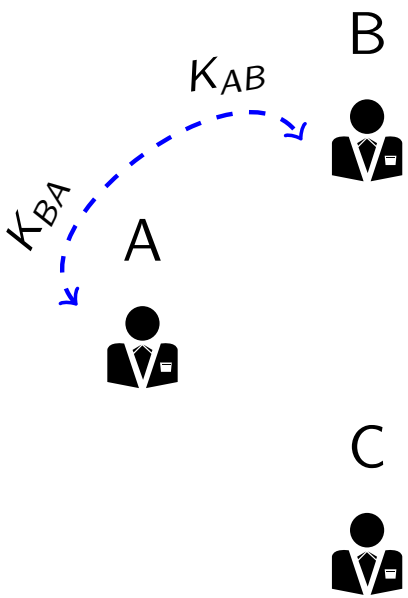
Symmetric DC-Nets (SDC-Nets)

[Cha88] - Dining Cryptographers Problem

SDC-Nets

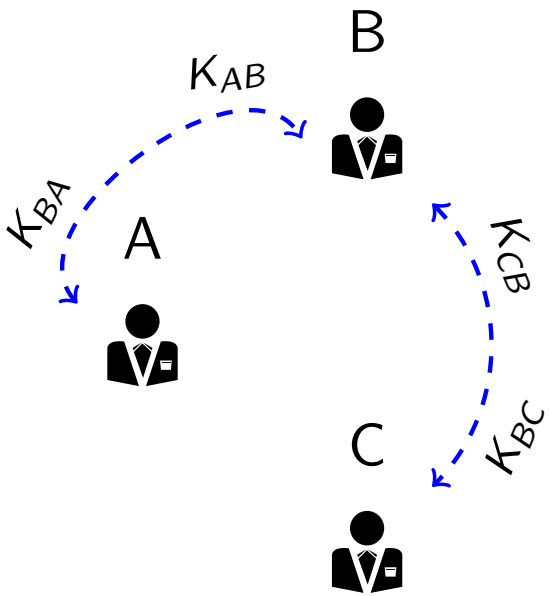
[Cha88] - Dining Cryptographers Problem



Agent

SDC-Nets

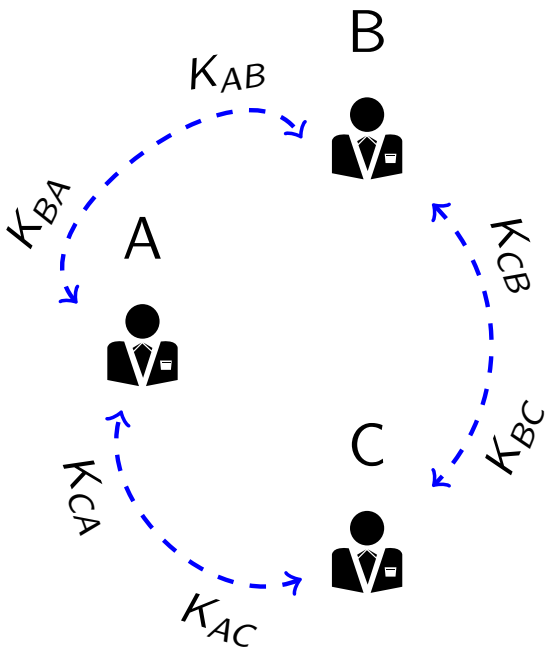
[Cha88] - Dining Cryptographers Problem



Agent

SDC-Nets

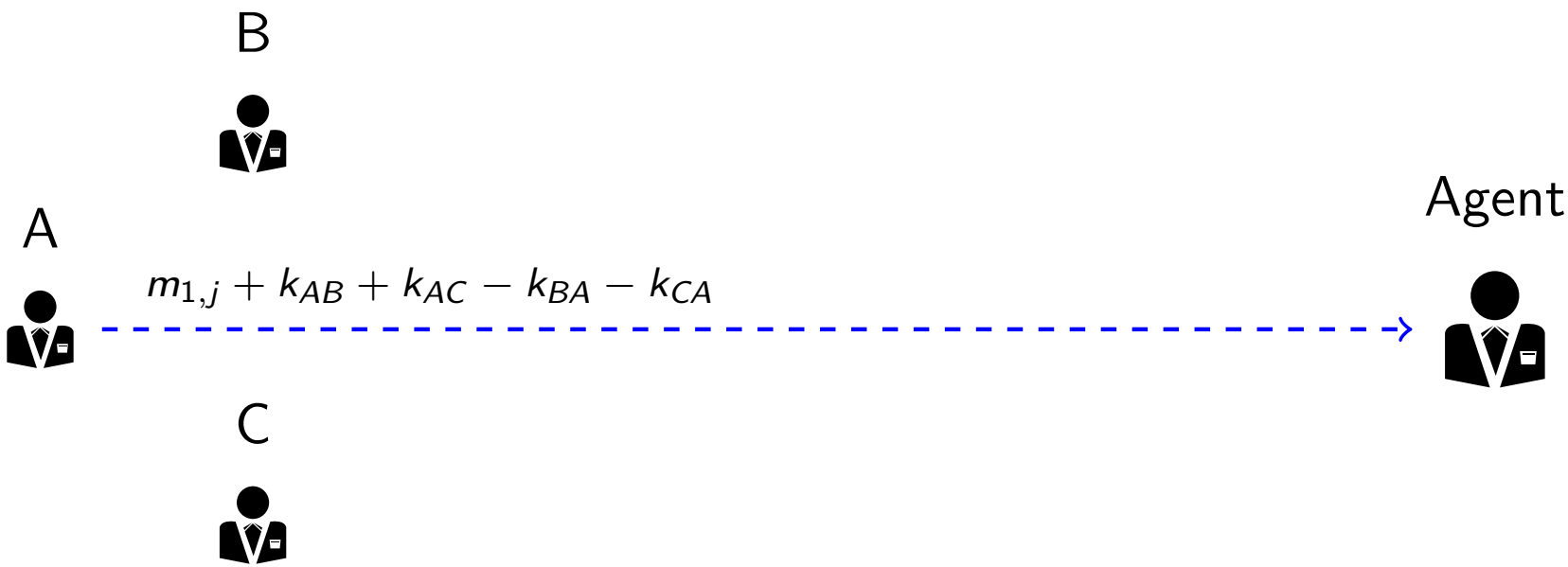
[Cha88] - Dining Cryptographers Problem



Agent

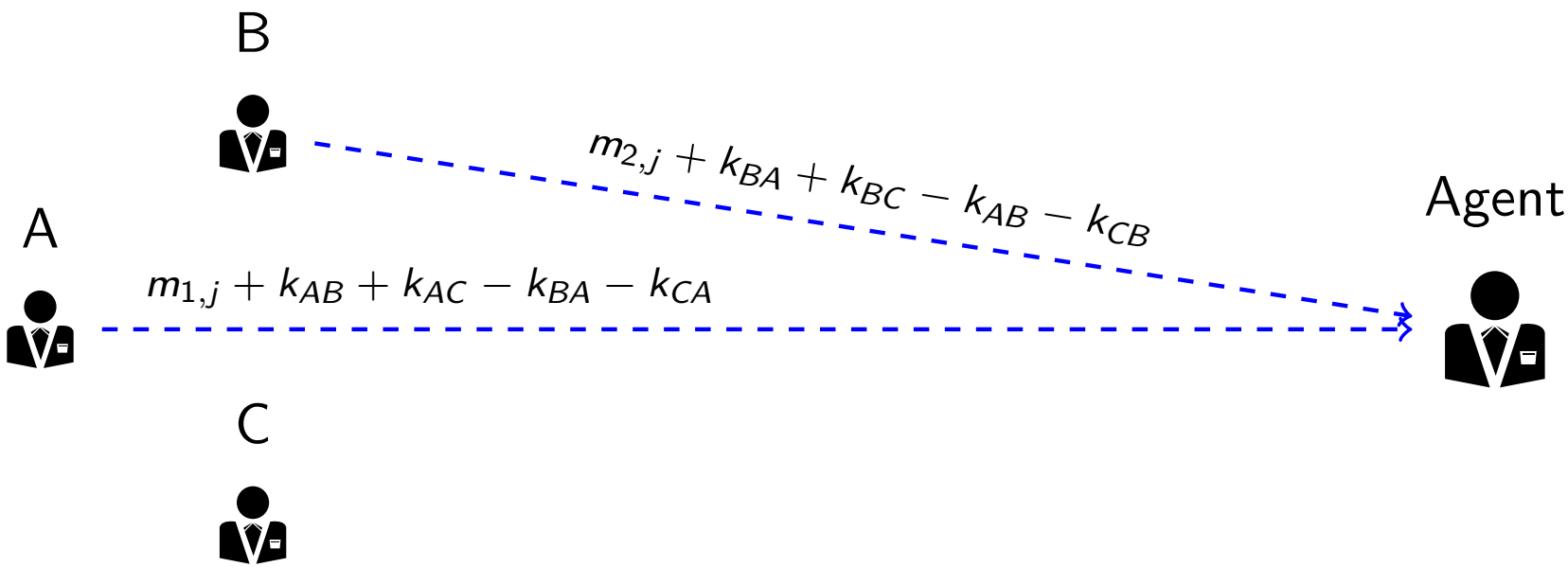
SDC-Nets

Unconditional Secure [Cha88]



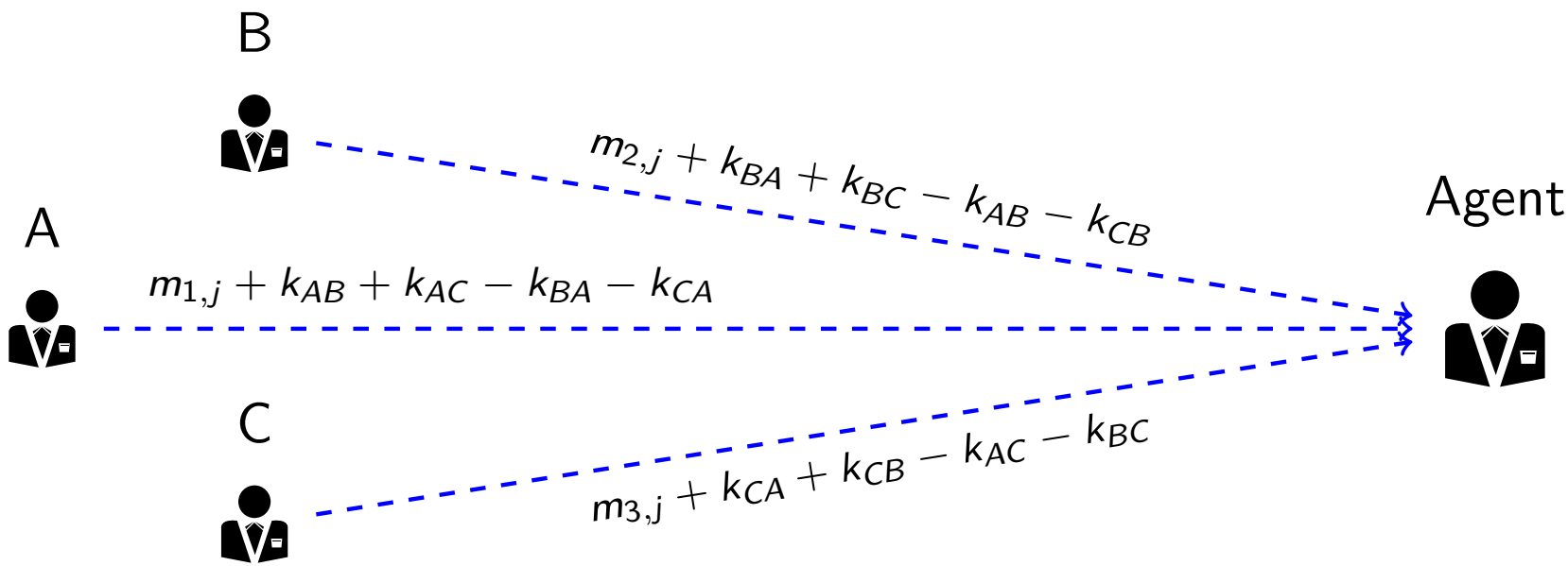
SDC-Nets

Unconditional Secure [Cha88]



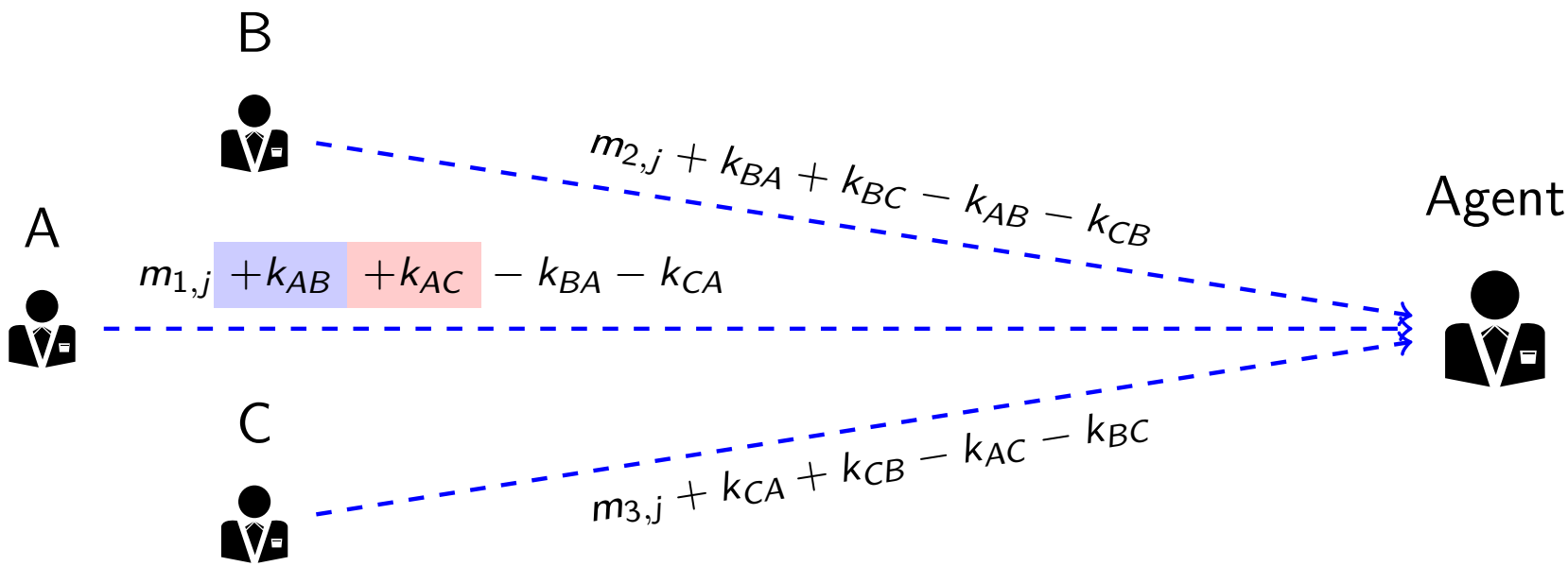
SDC-Nets

Unconditional Secure [Cha88]



SDC-Nets

Unconditional Secure [Cha88]



SDC-Nets

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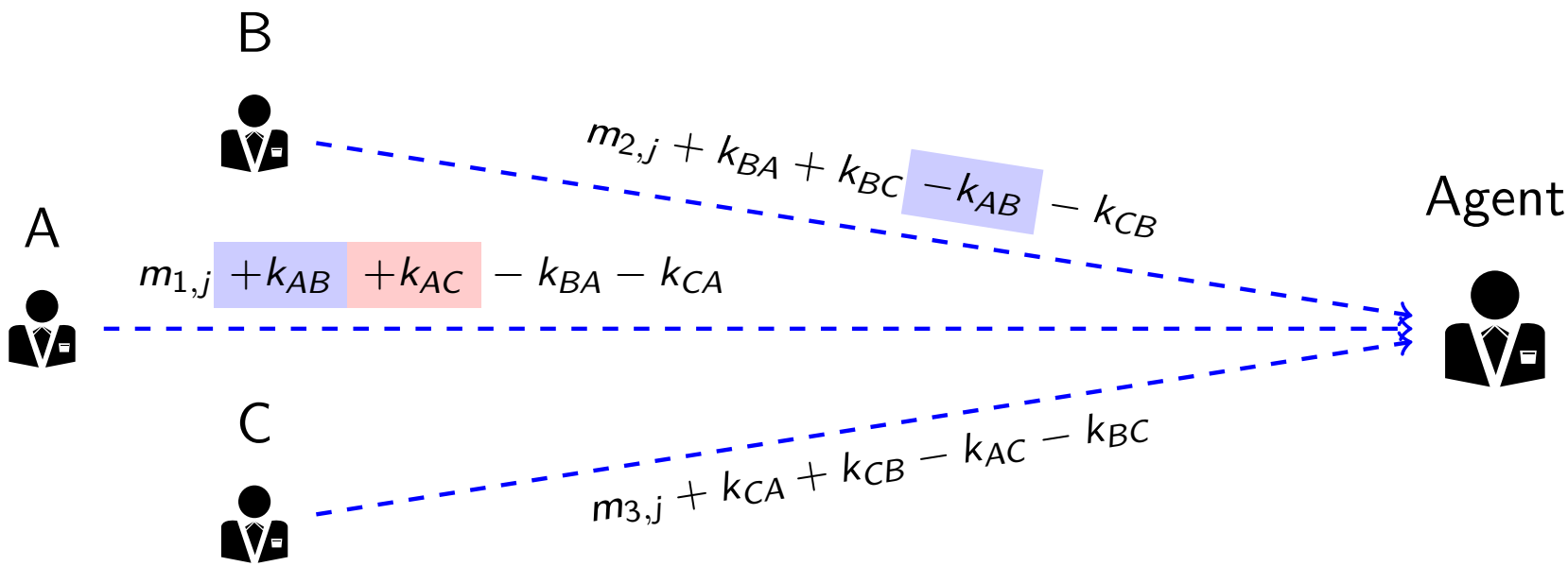

SDC-Nets

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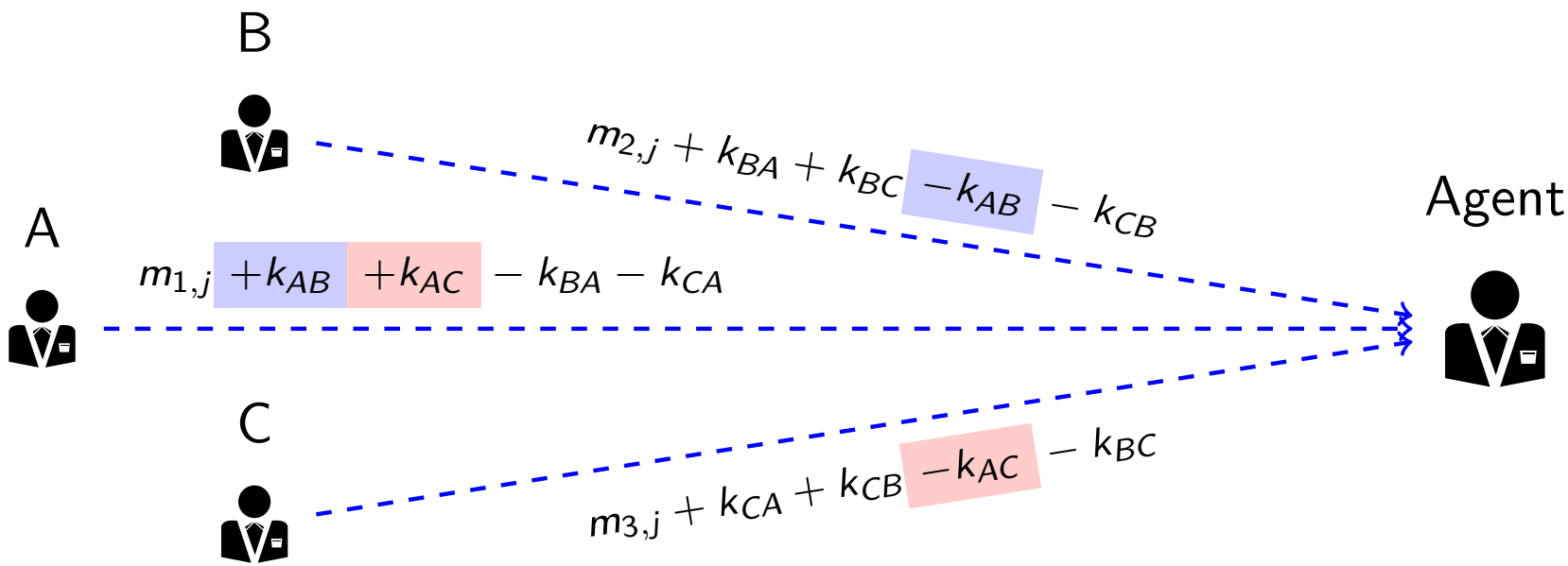
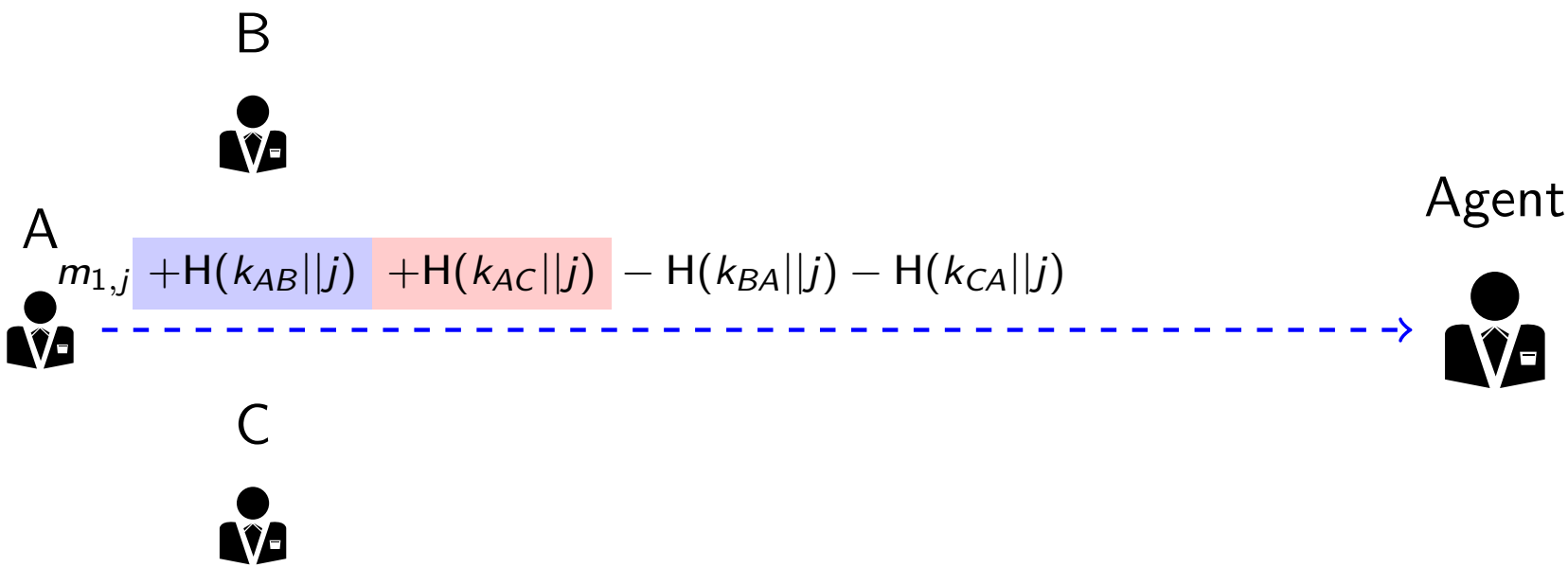


SDC-Nets

[GJ04]

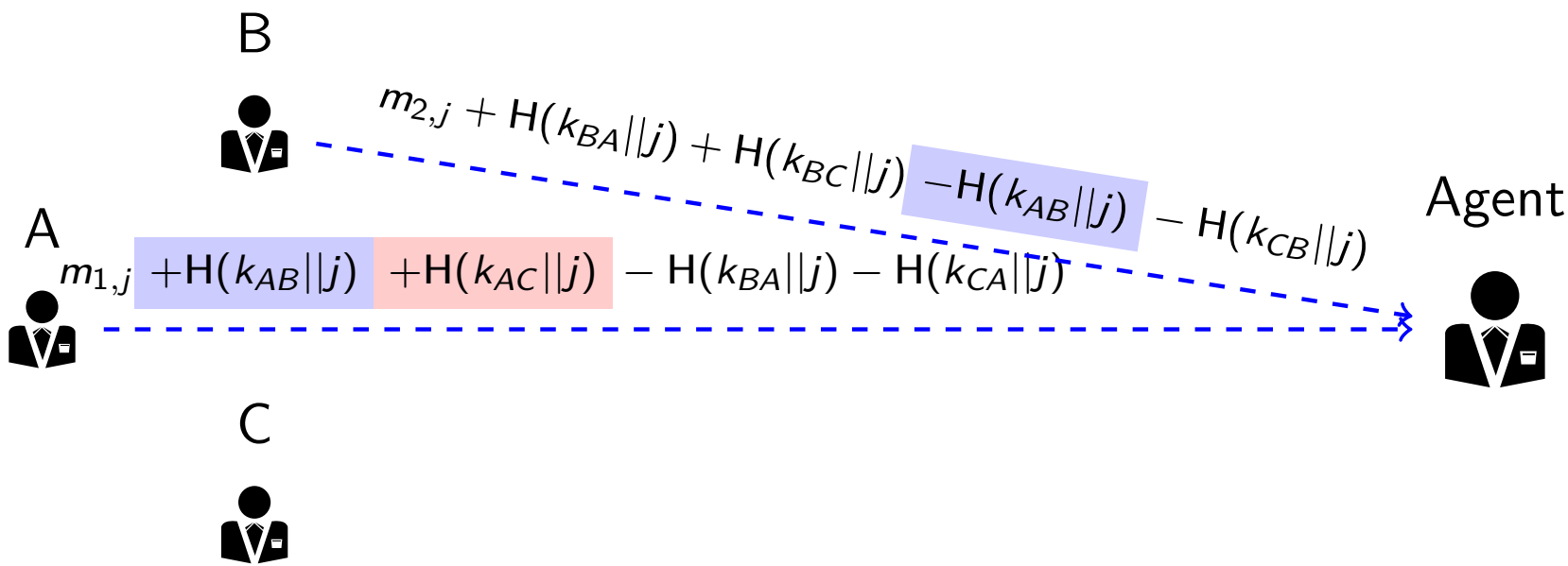
SDC-Nets

[GJ04]



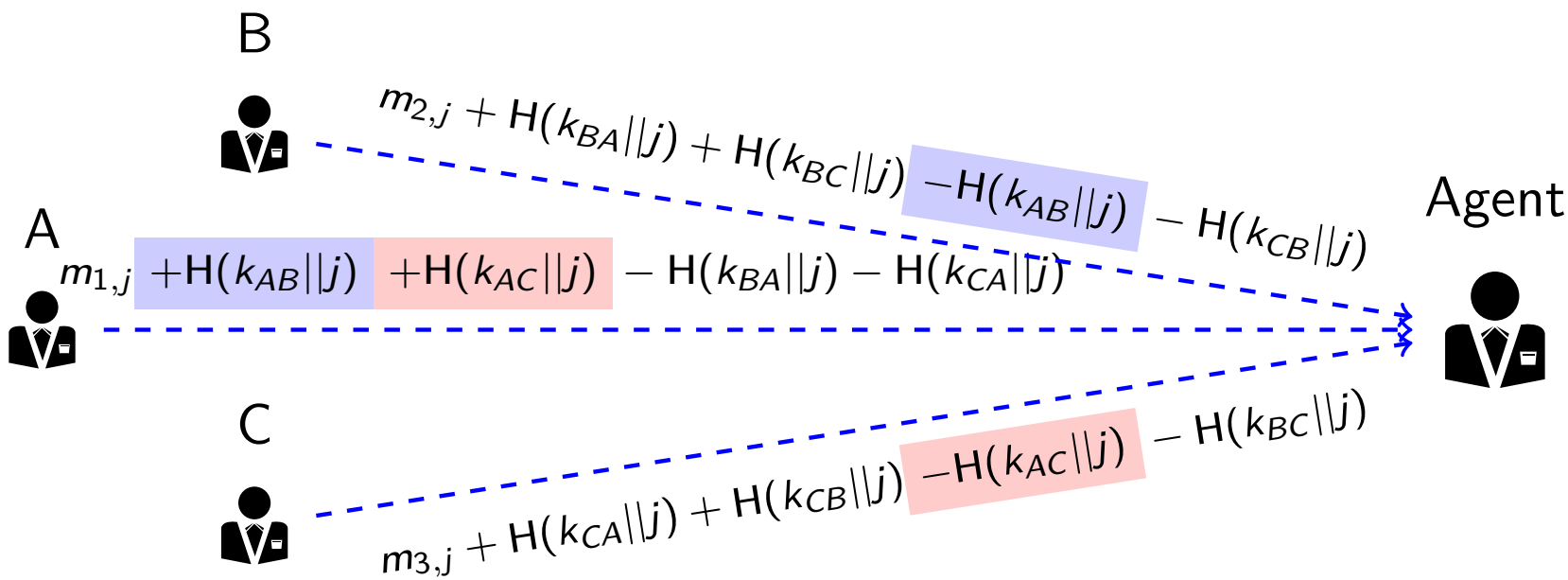
SDC-Nets

[GJ04]



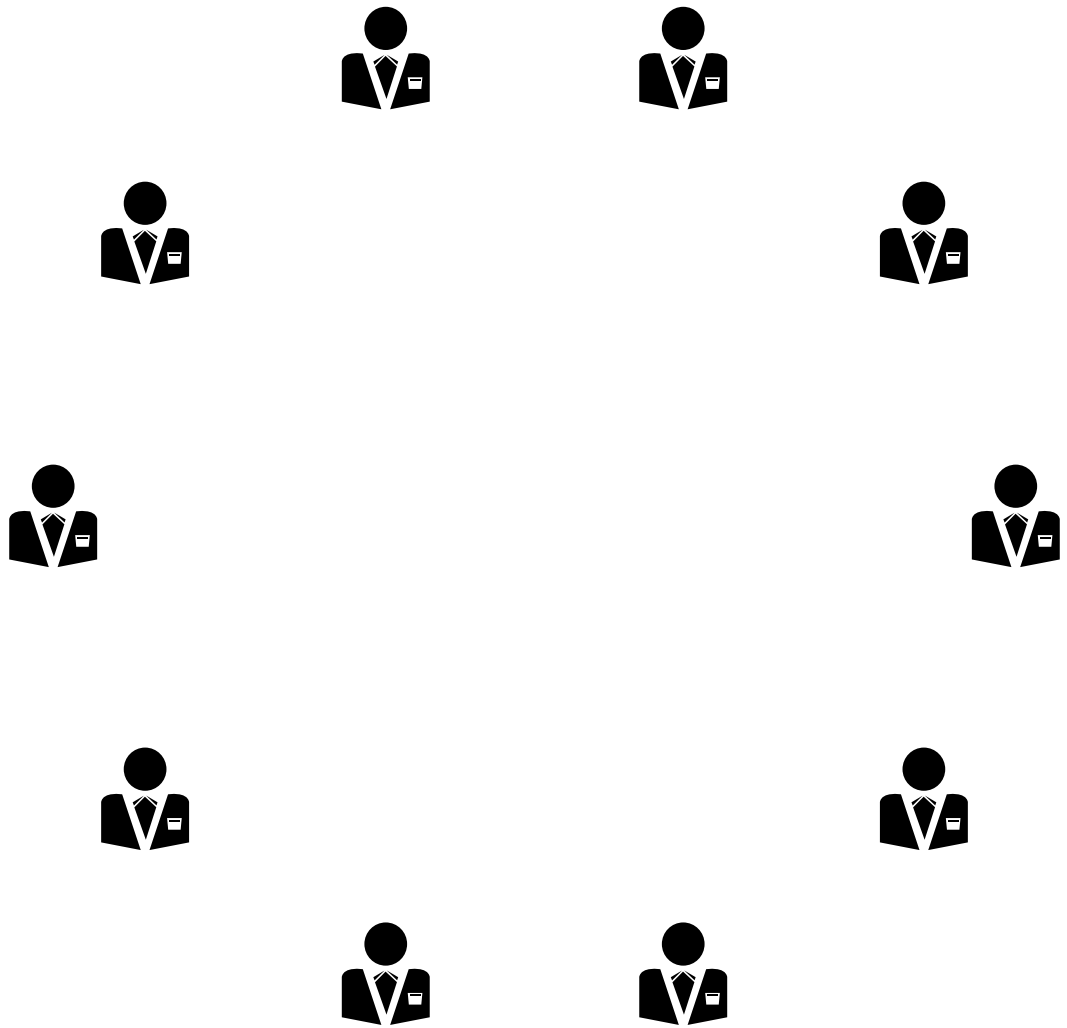
SDC-Nets

[GJ04]



SDC-Net

Keys for 10 users



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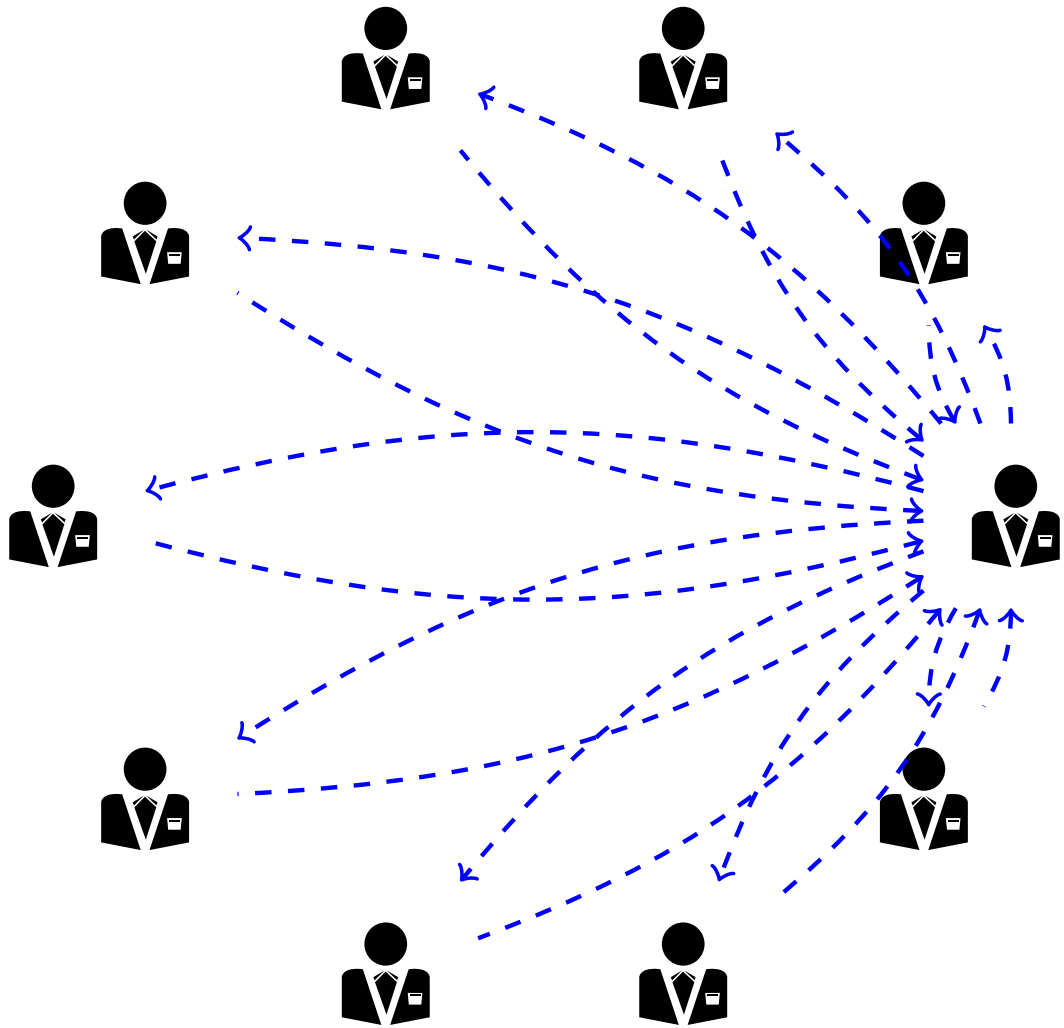
Keys for 10 users



SDC-Net

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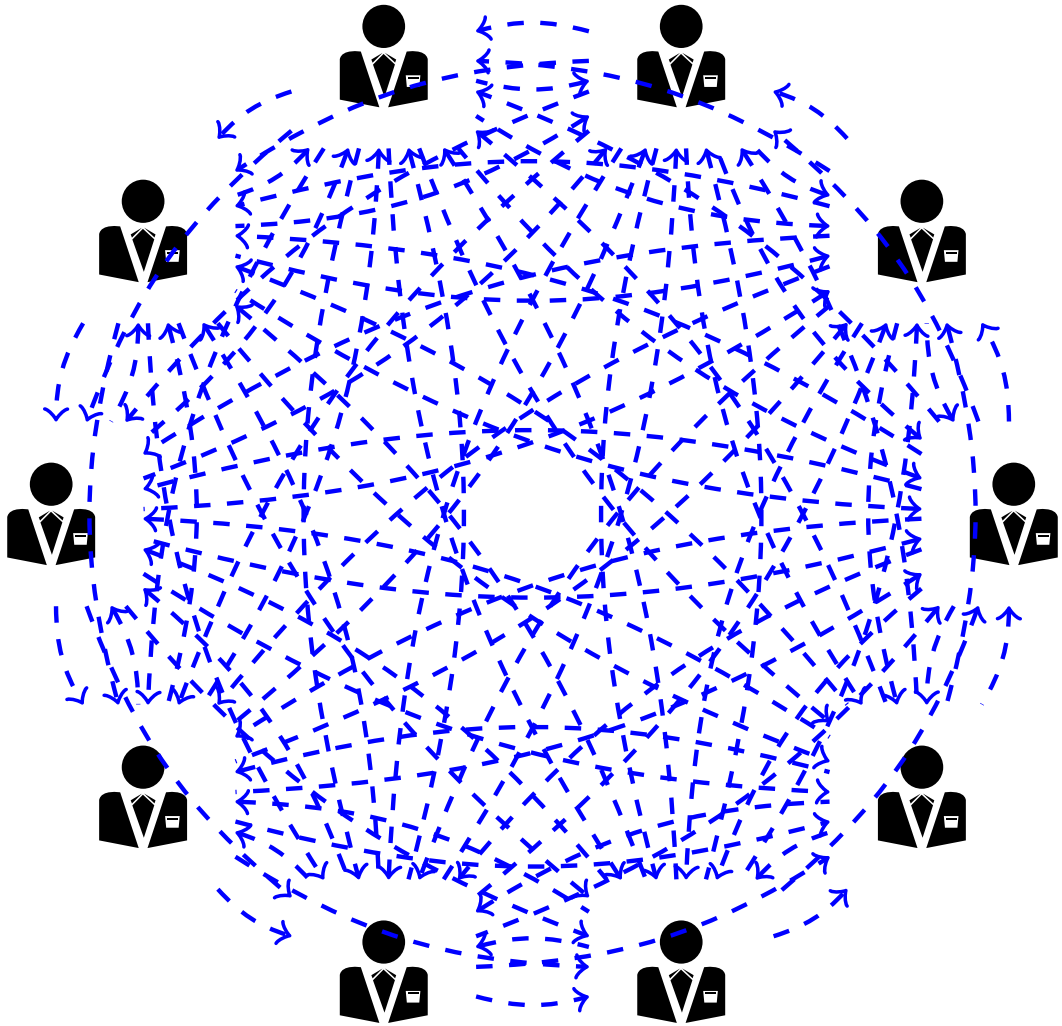
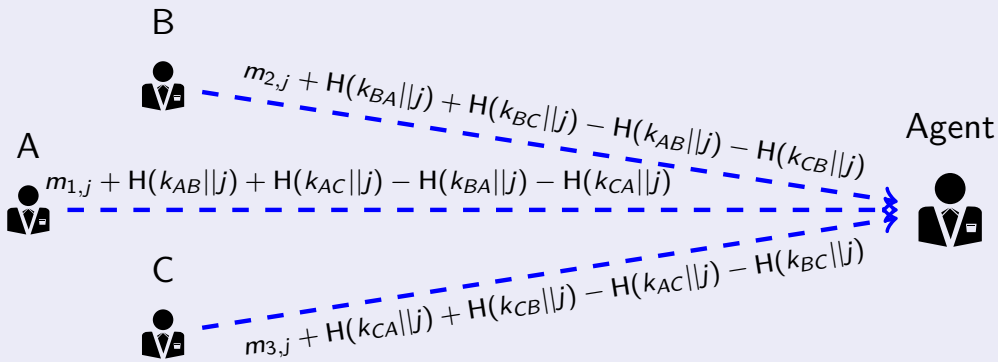
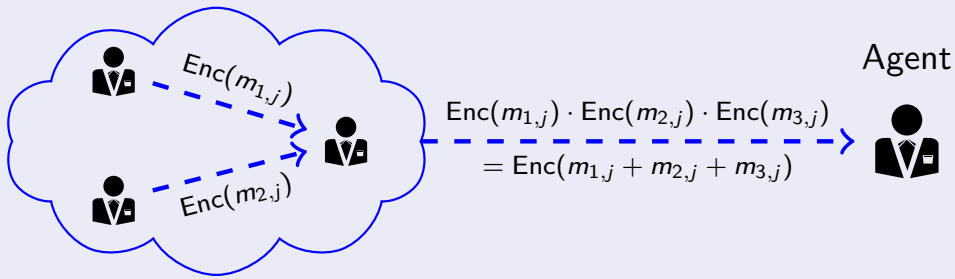


SDC-Nets versus AHEPs

Symmetric DC-Nets (SDC-Nets)



Additive homomorphic encryption primitives (AHEPs)



ADC-Net

Required Properties [BBM14; BM14b; BVM15]

Properties	**SDC-Nets**	**AHEPs**	**ADC-Net**
Collusion of $O(\tilde{i})$	✓	✗	
Set of trusted users	✓	✗	
Messages to the counting agent	✓	✗	
Minimum number of messages	✓	✓	
Scalable	✗	✓	
Permanent keys	✓	✓	
Based on trapdoors	✓	✓	
Keys stored per user	$2(\tilde{i}-1)$	1	
Total of keys	$O(\tilde{i}^2)$	2	
Polynomial time	✓	✓	
One cannot disrupt	✗	✗	
Verification as commitment	✗	✗	

ADC-Net

Required Properties [BBM14; BM14b; BVM15]

Properties	**SDC-Nets**	**AHEPs**	**ADC-Net**
Collusion of $O(\tilde{i})$	✓	✗	✓
Set of trusted users	✓	✗	✓
Messages to the counting agent	✓	✗	✓
Minimum number of messages	✓	✓	✓
Scalable	✗	✓	✓
Permanent keys	✓	✓	✓
Based on trapdoors	✓	✓	✓
Keys stored per user	$2(\tilde{i}-1)$	1	1
Total of keys	$O(\tilde{i}^2)$	2	$O(\tilde{i})$
Polynomial time	✓	✓	✓
One cannot disrupt	✗	✗	✓
Verification as commitment	✗	✗	✓

Interesting Results

Beyond the State of the Art

Result:

Asymmetric DC-Nets are abstractions of Symmetric DC-Nets

[BBM14]

Interesting Results

Beyond the State of the Art

Result:

Asymmetric DC-Nets are abstractions of Symmetric DC-Nets

[BBM14]

Result:

AHEPs are particular cases of ADC-Nets

Interesting Results

Beyond the State of the Art

Result:

Asymmetric DC-Nets are abstractions of Symmetric DC-Nets

[BBM14]

Result:

AHEPs are particular cases of ADC-Nets

Example

Paillier is a particular case of an ADC-Net

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Dataset

Raw Dataset ✗

The raw dataset has inconsistencies

Dataset

Raw Dataset ✗

The raw dataset has inconsistencies

Sanitized Dataset ✓

- 6 435 meters
- 25 726 rounds
- 165 546 810 measurements

Dataset

Raw Dataset ✗

The raw dataset has inconsistencies

Sanitized Dataset ✓

- 6 435 meters
- 25 726 rounds
- 165 546 810 measurements

Verification

Inconsistencies ⇒ measurements collected without verification

Comparison of requirements

between Privacy-Preserving Protocol (PPP)

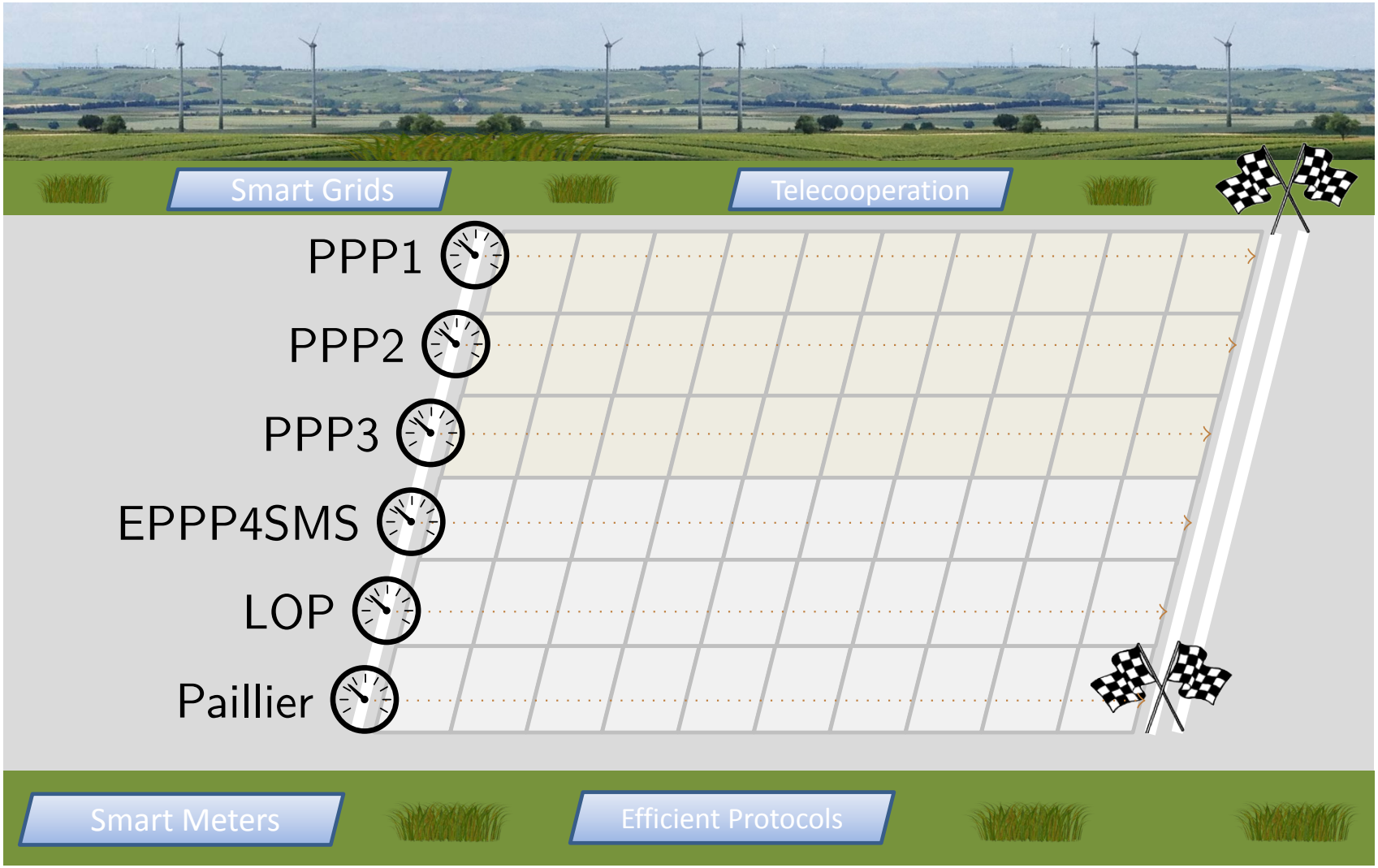
Protocol				Efficiency		
				Enc	Agg	Dec
PPP1	✓	✗	✗	$O(1)$	$O(\tilde{i})$	$O(\tilde{i})$
PPP2	✗	✓	✓	$O(\log(k))$	$O(\tilde{i})$	$O(k)$
PPP3	✓	✓	✓	$O(\log(k))$	$O(\tilde{i})$	$O(\log(k))$
EPPP4SMS	✓	✓	✓	$2O(\log(k))$	$O(\tilde{i})$	$O(\log(n))$
LOP - SDC-Net	✓	✗	✗	$O(\tilde{i})$	NA	$O(\tilde{i})$
Paillier - AHEP	✓	✗	✗	$O(\log(n))$	$O(\tilde{i})$	$O(\log(n))$

IEEE Trans. Smart Grid - Impact Factor: 4.334

"EPPP4SMS: Efficient Privacy-Preserving Protocol for Smart Metering Systems and Its Simulation Using Real-World Data"

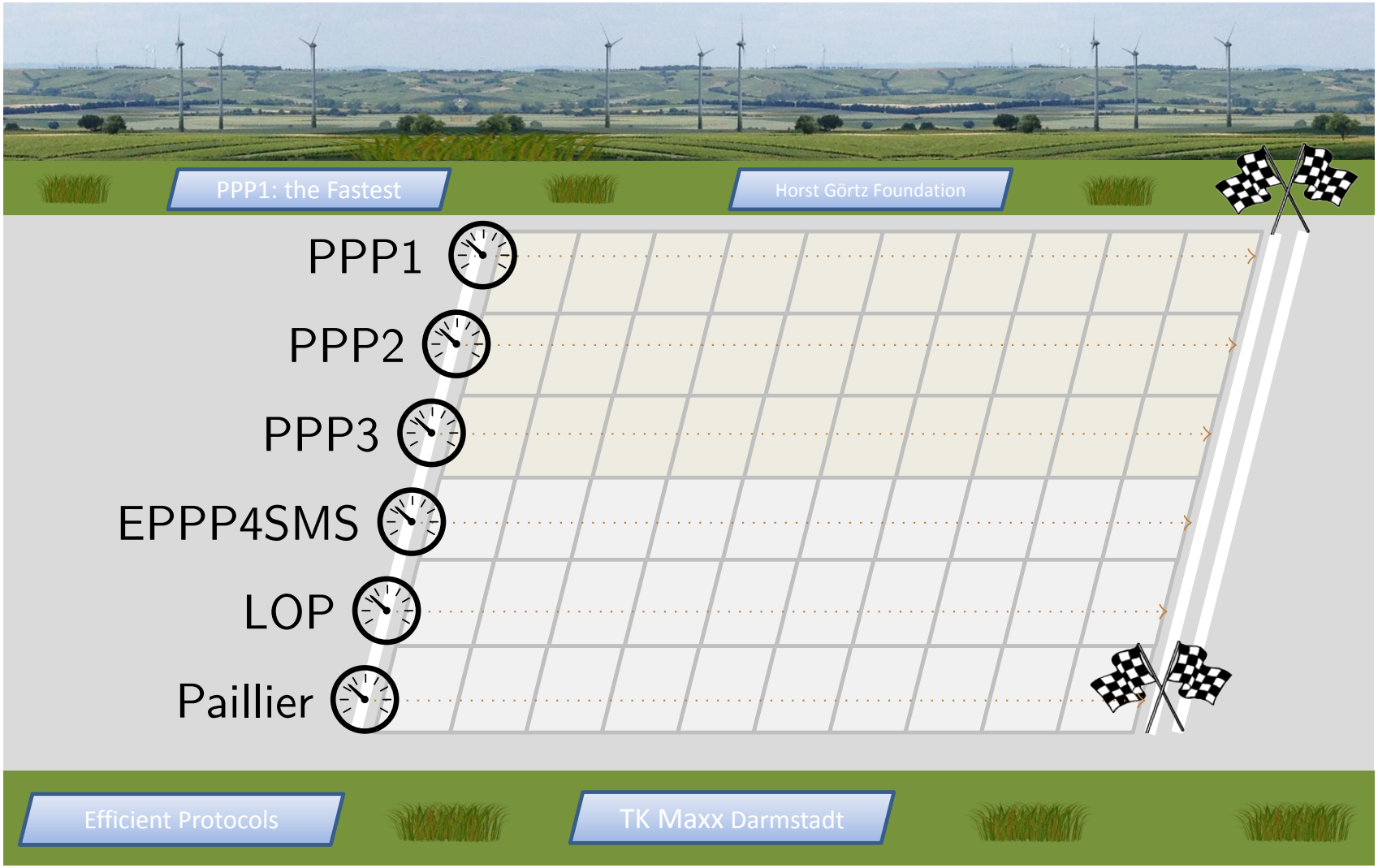
Overall Performance

Race protocols



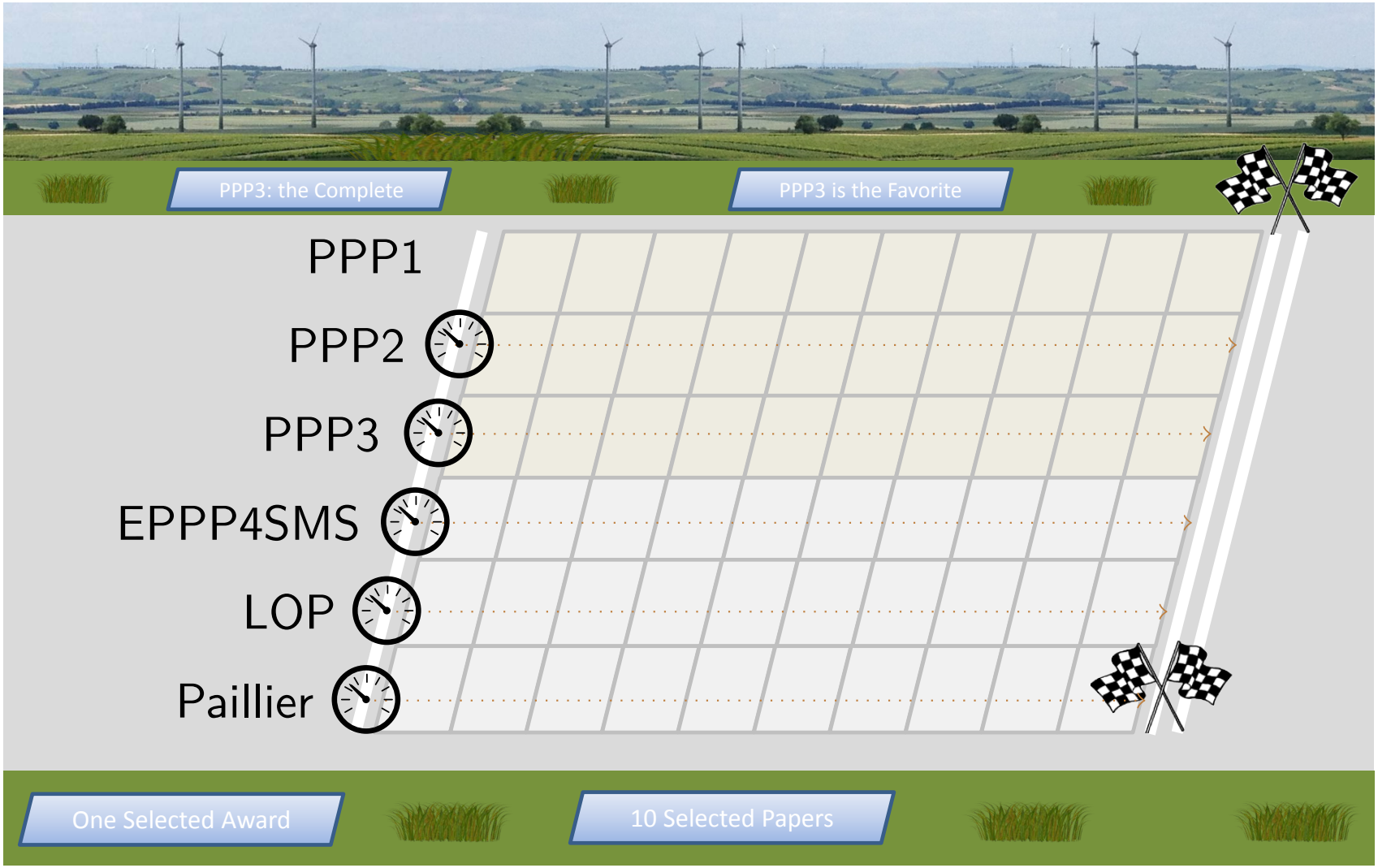
Overall Performance

Race protocols



Overall Performance

Race protocols



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Conclusion

- Privacy-Preserving Protocols (PPPs) only work for large aggregations

Conclusion

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- PPP1 has the fastest Enc ($m_{i,j}$)

Conclusion

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- PPP2 and PPP3 are exponentially faster than others

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- PPP4 is resistant against quantum attacks

Conclusion

- PPPs only work for large aggregations
- PPP1 has the fastest Enc ($m_{i,j}$)
- PPP2 and PPP3 are exponentially faster than others
- PPP4 is resistant against quantum attacks
- The concept of ADC-Nets is introduced

Selected Publications

Journal Papers

[BM14b]	Fábio Borges and Max Mühlhäuser. EPPP4SMS: efficient privacy-preserving protocol for smart metering systems and its simulation using real-world data. *IEEE trans. smart grid*, 5(6):2701–2708, 2014
Impact Factor	4.334
h5-index	54
[BSM14]	Fábio Borges, Raqueline A. M. Santos, and Franklin L. Marquezino. Preserving privacy in a smart grid scenario using quantum mechanics. *Security and communication networks*:n/a–n/a, 2014
Impact Factor	0.433
h5-index	19
[LBPN12]	Pedro Lara, Fábio Borges, Renato Portugal, and Nadia Nedjah. Parallel modular exponentiation using load balancing without precomputation. *Journal of computer and system sciences*, 78(2):575–582, 2012
Impact Factor	1.091
h5-index	30

Selected Publications

Award

[BBM14] Fábio Borges, Johannes Buchmann, and Max Mühlhäuser. Introducing asymmetric dc-nets. In *Communications and network security (CNS), 2014 IEEE conference on*, 2014, pages 508–509

Best Poster Award - IEEE Communications Society

Selected Publications

Conference Papers

[BBM14] Fábio Borges, Johannes Buchmann, and Max Mühlhäuser. Introducing asymmetric dc-nets. In *Communications and network security (CNS), 2014 IEEE conference on*, 2014, pages 508–509

[BM14a] Fábio Borges and Leonardo A. Martucci. iKUP keeps users' privacy in the smart grid. In *Communications and network security (CNS), 2014 IEEE conference on*, 2014, pages 310–318

[BDBBM14] Fábio Borges, Denise Demirel, Leon Böck, Johannes Buchmann, and Max Mühlhäuser. A privacy-enhancing protocol that provides in-network data aggregation and verifiable smart meter billing. In *Computers and communication (ISCC), 2014 IEEE symposium on*, 2014, pages 1–6

[BMBM14] Fábio Borges, Leonardo A. Martucci, Filipe Beato, and Max Mühlhäuser. Secure and privacy-friendly public key generation and certification. In *Trust, security and privacy in computing and communications (TrustCom), 2014 IEEE 13th international conference on*, 2014, pages 114–121

[BMM12] Fábio Borges, Leonardo A. Martucci, and Max Mühlhäuser. Analysis of privacy-enhancing protocols based on anonymity networks. In *Smart grid communications (SmartGridComm), 2012 IEEE third international conference on*, 2012, pages 378–383

[BPP12] Fábio Borges, Albrecht Petzoldt, and Renato Portugal. Small private keys for systems of multivariate quadratic equations using symmetric cryptography. In *XXXIV CNMAC - congrasso nacional de matemática aplicada e computacional*. Águas de Lindóia - SP, 2012, pages 1085–1091

[BVM15] Fábio Borges, Florian Volk, and Max Mühlhäuser. Efficient, verifiable, secure, and privacy-friendly computations for the smart grid. In *Innovative smart grid technologies conference (ISGT), 2015 IEEE power energy society*, 2015, pages 1–5

Outlook

ADC-Nets can be used in applications that require:

- SDC-Nets

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  - mobile sensing
  - multi-party computation
  - image processing

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Thank You!

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All comments and suggestions are welcomed.
Contact: borges@lncc.br

Contributions

1. Detection of profile in protocols based on noise
2. Reasons for frequent measurements
   - Detection of fraud and energy loss
   - Virtualization of a commodity network
   - Fair Distribution (challenge)
3. Minimal requirements for PPPs
4. Limitations for all PPPs
   - Algebraic properties
   - Probabilistic properties
5. The concept of ADC-Nets
   - Abstractions of SDC-Nets
   - Generalization of AHEPs
6. Four new PPPs
   - PPP1 is the fastest
   - PPP2 uses commitment with elliptic curve
   - PPP3 is an ADC-Net
   - PPP4 is resistant against quantum attacks
7. An SDC-Net that behaves as AHEPs
8. Detection of inconsistencies in the dataset
9. Theoretical analysis validated with simulation

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