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Physical Attestation of Cyber Processes in the Smart Grid

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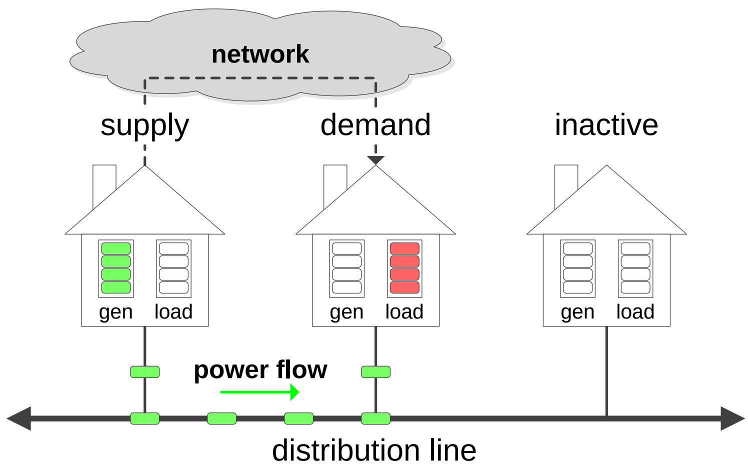
FREEDM Systems Center

The FREEDM (Future Renewable Electric Energy Delivery and Management) Concept

- Distributed Grid Intelligence (DGI)
  - People share energy resources
  - Neighborhood or industrial level
  - Where is the centralized controller?
  - Peer-to-peer

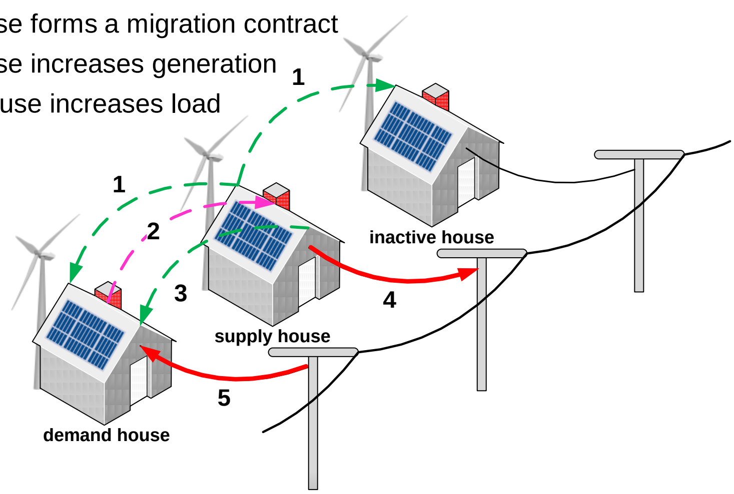
FREEDM Systems Center

Smart Neighborhood



Power Migrations

1. Supply house advertises its excess generation
2. Demand house requests power from supplier
3. Supply house forms a migration contract
4. Supply house increases generation
5. Demand house increases load



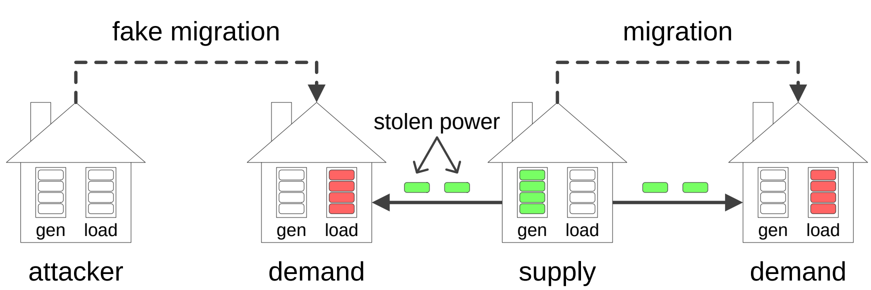
New Threats - Distributed System

- The current electric power grid relies on the notion of a centralized power authority.
- No centralized authority is involved with the distributed process of power migrations.
- A compromised house can trick its peers into making bad power migrations in the absence of the centralized authority.

Fake Supply Attack

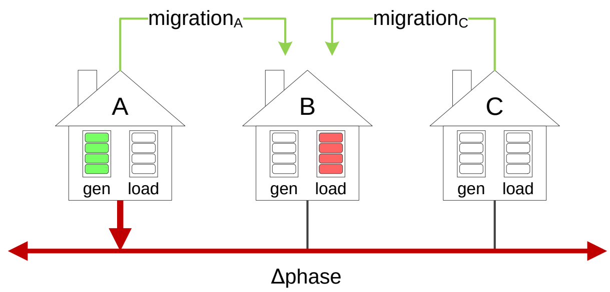
Consider an attack that removes one step from the system operation:

1. Supply house advertises its excess generation
2. Demand house requests power from supplier
3. Supply house forms a migration contract
4. ~~**Supply house increases generation**~~
5. Demand house increases load



Concurrent Fake Supply Attack

- House C launches a fake supply attack during a migration from A:



- During the attack, the low-level view of house B is:

- This view is consistent with either $increase_A$ or $increase_C$!

Information Flow Models

– *Non-Interference*
  - High-level events do not interfere with the low level outputs

– *Non-Inference*
  - Removing high-level events leaves a valid system trace

– *Non-Deducibility*
  - Low-level observation is compatible with any of the high-level inputs.

Typically we use these to blind an attacker, here we use them to model a STUXNET-like attack

Nondeducible Attack

- Definition:
  A low-level view of a system is *nondeducible* if the view is consistent with all permutations of high-level commands.

- Theorem:
  An attacker who launches a fake supply attack concurrent with another migration in the system is *nondeducible* and thus unidentifiable.

Solutions in Literature

- Tamper Resistance:
  Prevent an attack using compromise-resistant hardware.

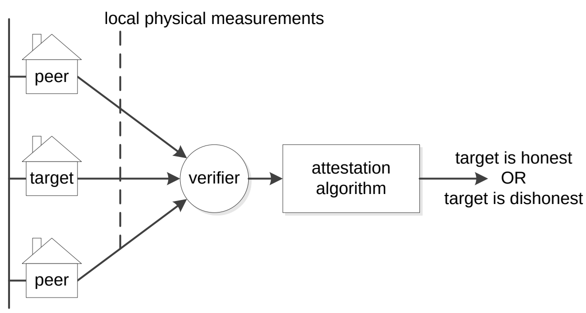
- Bad Data Detection:
  Detect malicious meter readings at a centralized controller.

- Distributed Diagnosis:
  Detect a fault using peer evaluations in a distributed system.

- Remote Attestation:
  Detect a compromised node using a challenge-response protocol.

Physical Attestation

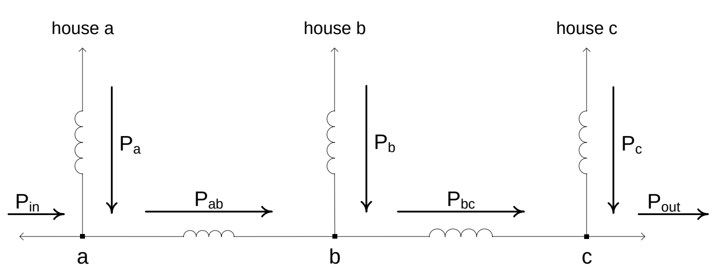
- A verifier checks if another cyber process is compromised using physical measurements.



- Similar to a remote attestation algorithm that uses the physical layer as a shared memory.

Conservation of Power

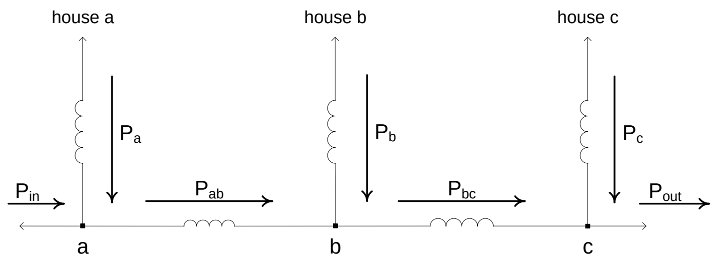
- Conservation of Power at b: $\{I_b : P_{ab} + P_b - P_{bc} = 0\}$



- I_b is an invariant that must be true for the physical system.
- If I_b is violated, then at least one house must be dishonest.

Physical Measurements

- The invariant is instantiated using measurements from each house:



$$\{I_b : P_{ab} + P_b - P_{bc} = 0\}$$

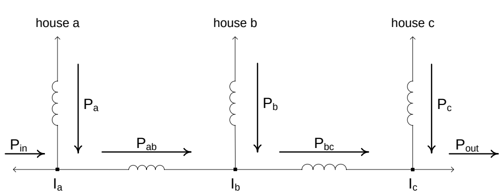
$$P_{ab} = \frac{V_a V_b}{X_{ab}} sin(\theta_b - \theta_a)$$

$$P_{bc} = \frac{V_b V_c}{X_{bc}} sin(\theta_c - \theta_b)$$

House	Measurements
A	$V_a \theta_a$
B	$P_b V_b \theta_b$
C	$V_c \theta_c$

Impact of Compromised Node

- Assume *b* is malicious and the other two houses are honest.



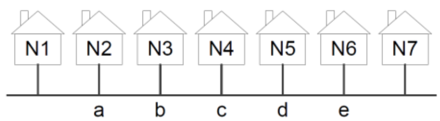
- A set of invariants are violated when *b* falsifies its values:

Falsified Values	Violated Invariants
P_b	I_b
$V_b \theta_b$	$I_a I_b I_c$
$P_b V_b \theta_b$	$I_a I_c$

- The dishonest house is the midpoint of each violation set.

Unique Violation Pattern

- It requires observations from 7-houses to find a unique violation pattern:



- It is not possible to produce a unique pattern with fewer observations.
- This set of observations can be used to detect when house 4 performs a fake supply attack

N	Falsified	Violations
1	$V_1\theta_1$	I_a
2	P_2	I_a
	$V_2\theta_2$	$I_a I_b$
	$P_2 V_2\theta_2$	I_b
3	P_3	I_b
	$V_3\theta_3$	$I_a I_b I_c$
	$P_3 V_3\theta_3$	$I_a I_c$
4	P_4	I_c
	$V_4\theta_4$	$I_b I_c I_d$
	$P_4 V_4\theta_4$	$I_b I_d$
5	P_5	I_d
	$V_5\theta_5$	$I_c I_d I_e$
	$P_5 V_5\theta_5$	$I_c I_e$
6	P_6	I_e
	$V_6\theta_6$	$I_d I_e$
	$P_6 V_6\theta_6$	I_d
7	$V_7\theta_7$	I_e

Attestation Algorithm

Algorithm 1: Secure Power Calculation

Data: Index t of the node to attest
Data: The *time* of the attestation
Data: A small tolerance ϵ
Result: Actual generation P_t at node t

get values $\{\hat{P}_{t-2}, \ldots, \hat{P}_{t+2}\}$ for given *time* — // get cyber message history
get values $\{V_{t-3}\theta_{t-3}, \ldots, V_{t+3}\theta_{t+3}\}$ for given *time* — // get physical meter readings
for $i \leftarrow t-2$ **to** $t+2$ **do** — // evaluate each invariant
  $P_{i-1,i} \leftarrow \frac{V_{i-1}V_i}{X_{i-1,i}} sin(\theta_i - \theta_{i-1})$
  $P_{i,i+1} \leftarrow \frac{V_i V_{i+1}}{X_{i,i+1}} sin(\theta_{i+1} - \theta_i)$
  if $|P_{i-1,i} + \hat{P}_i - P_{i,i+1}| < \epsilon$ **then**
    $I_i \leftarrow true$
  else
    $I_i \leftarrow false$

if $\neg I_{t-1}$ **and** $\neg I_{t+1}$ **OR** $\neg I_t$ **and** $(\forall k \neq t)(I_k)$ **then** — // check the violation pattern
  $P_{t-1,t} \leftarrow P_{t-2,t-1} + \hat{P}_{t-1}$
  $P_{t,t+1} \leftarrow P_{t+1,t+2} - \hat{P}_{t+1}$
  return $P_{t,t+1} - P_{t-1,t}$ — // case when t is dishonest
else
  return $\hat{P}_t$ — // case when t is honest

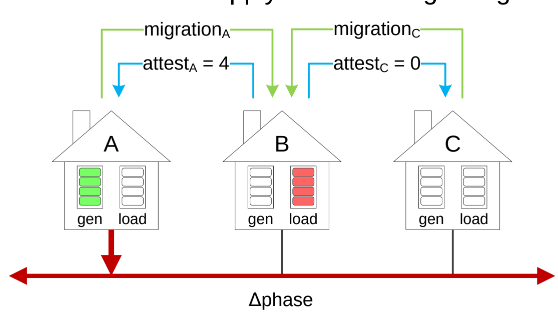
System Modifications

<u>Two modifications make the fake supply attack deducible:</u>

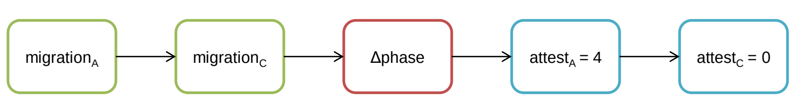
1. Supply house advertises its excess generation
2. Demand house requests power from supplier
3. Supply house forms a migration contract
4. Supply house increases generation
5. ***Demand house performs attestation as a verifier***
6. ***If attestation passes, demand house increases load***

Deducible Fake Supply Attack

- House C launches a fake supply attack during a migration from A:



- During the attack, the low-level view of house B is:



- This view is ***not*** consistent with *increase*$_C$ and therefore deducible!

Conclusion

- A software solution to compromised peers that mitigates the need for new hardware.
- More powerful than remote attestation since an attacker cannot hide the effect of its actions on the physical layer.
- Current algorithm is limited to one attack type on linear physical topologies.
- Shows new kinds of vulnerabilities induced by peer-to-peer energy and power management

http://freedm.ncsu.edu