New Modes of Encryption - A Perspective and a Proposal

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Outline

1. Security Claims
2. Operational Claims
3. Evidence
4. Examples: XCBC, XECB-MAC and PM-XOR
5. Proposal: Three* Distinct Mode Candidates
6. Intellectual Property Status

1. Security Claims for Modes of Encryption

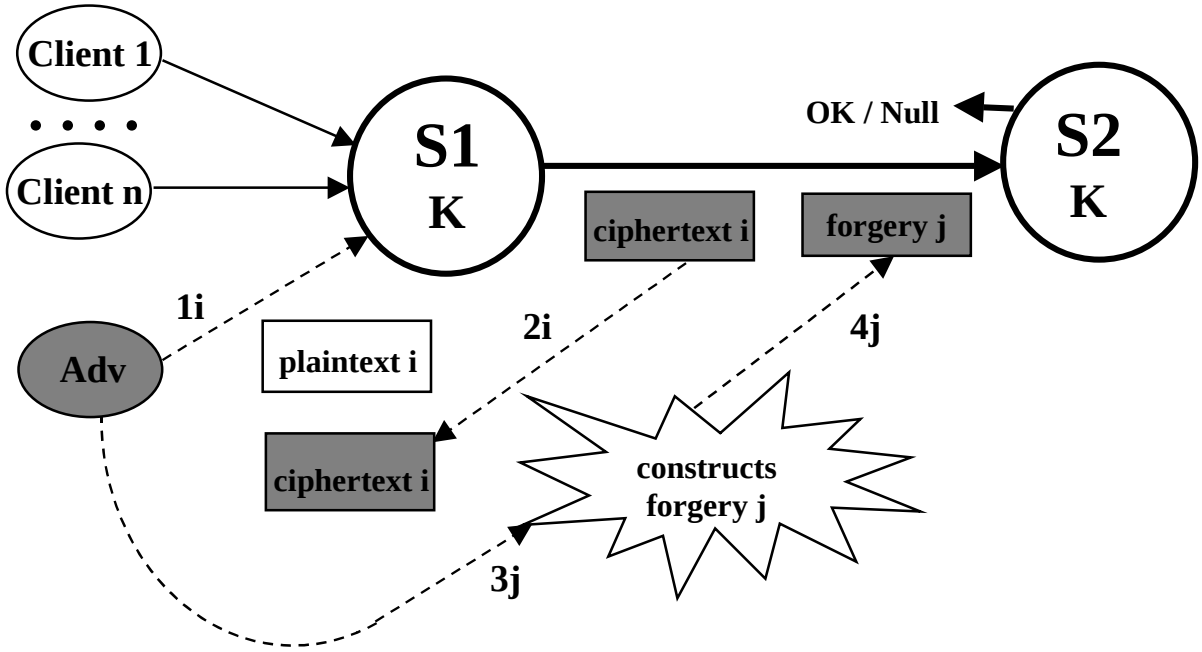
1. ***Claim*** = a security notion supported by
   a mode or scheme of encryption
2. Security ***Notion*** = < security goal, attack characteristics>

3. Security ***Goal***: confidentiality, integrity (authenticity), common
   - Examples:
     - confidentiality: indistinguishability (IND)
     - integrity: resistance to existential forgery (EF)
     - common: resistance to key searches (KS)
     - combinations

4. ***Attack Characteristics*** (models)
   - Examples:
     - Chosen (Known) Plaintext
     - Ciphertext-only
     - Chosen ciphertext
     - combinations

Example of a Chosen-Plaintext Attack

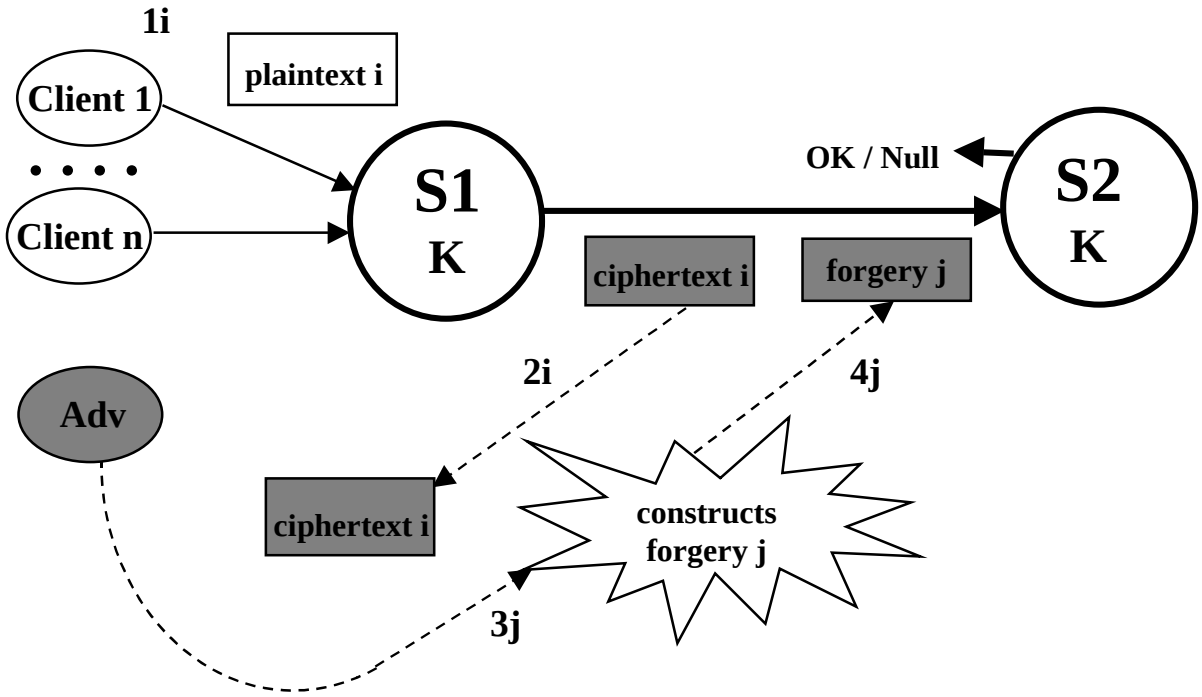
Distributed Service: S (S1, S2), shared key K; Clients: Client 1. … Adv, …, Client n
Adversary: Adv



In attack scenario:
S1 becomes an Encryption Oracle
S2 becomes a Decryption Oracle

Example of Ciphertext-only Attack

Distributed Service: S (S1, S2), shared key K; Clients: Client 1,…, Client n
Adversary: Adv is not a client



In attack scenario:
No Encryption Oracle: plaintext i is r.u.d
(Adv known absolutely nothing about plaintext i)
S2 becomes a Decryption Oracle

Example of Integrity Goals

Existential Forgery **protection (EF) : Pr[D_K(forgery) =/= Null] is negligible**

Other Integrity Notions: constraints on D_K(forgery) =/= Null

Examples:

Non-malleability **(NM) :**
given ciphertext challenge y whose plaintext x may be unknown, find forgery of the same length as y :
Pr [D_K(forgery) =/= Null and Relationship(D_K(forgery), x)] is negligible

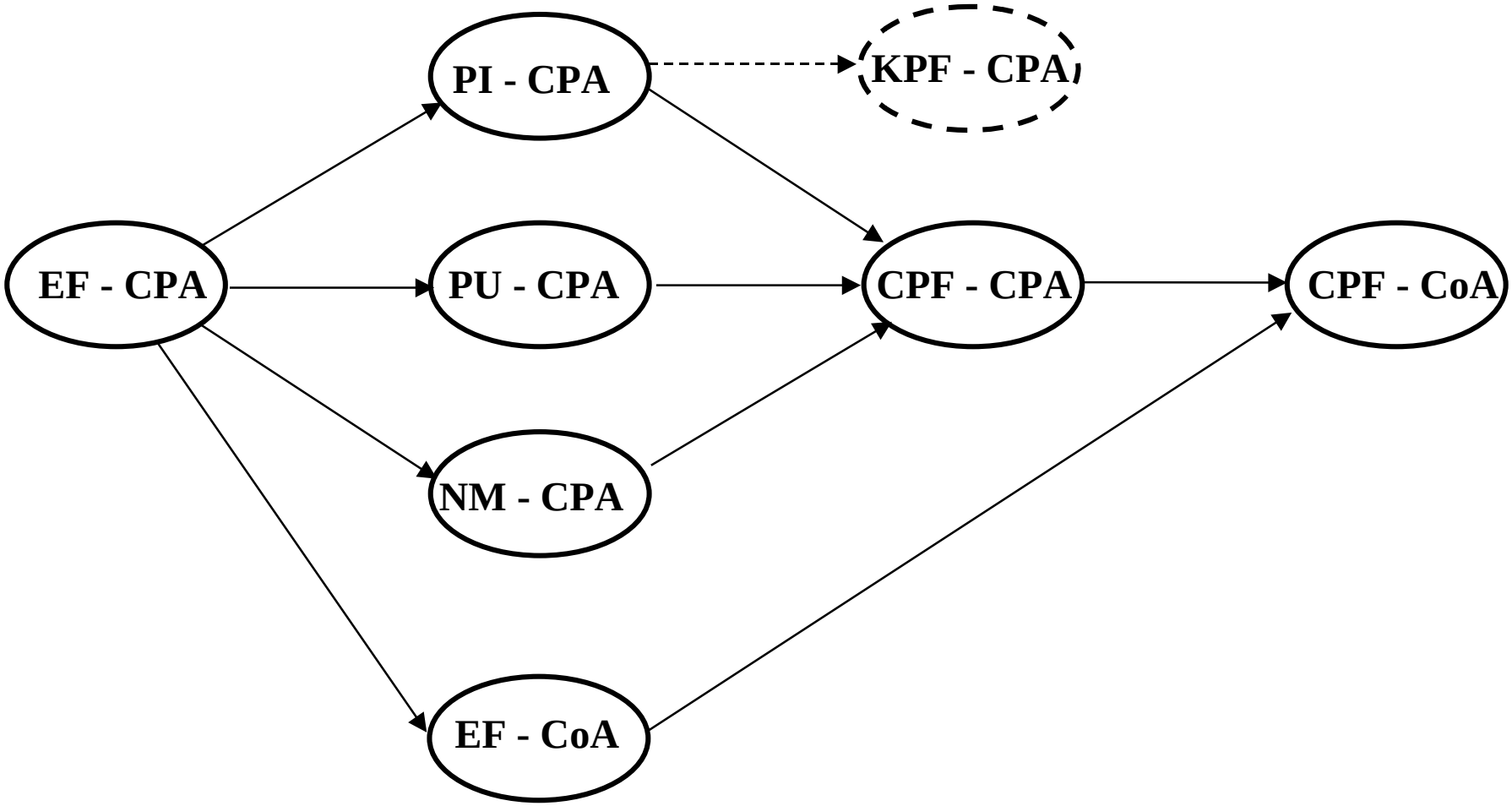
Integrity of Plaintexts **(PI) :**
Pr [D_K(forgery) =/= Null and D_K(forgery) =/= plaintexts encrypted before] is negligible

Assurance of *Plaintext Uncertainty* (PU) :
Pr [D_K(forgery) =/= Null => D_K(forgery) =/= plaintexts encrypted before and *is unknown*] is close to 1

Protection against *Chosen-Plaintext Forgery* (CPF) : given a chosen plaintext challenge *x*,
Pr [D_K(forgery) =/= Null and D_K(forgery) = *x* =/= plaintexts encrypted before] is negligible

Note: **some constraints may be integrity counter-intuitive; e.g.,**
assurance of *Known-Plaintext Forgery* (KPF)
Pr [D_K(forgery) =/= Null => D_K(forgery) is *known*] is close to 1.

Relationships among Integrity Notions



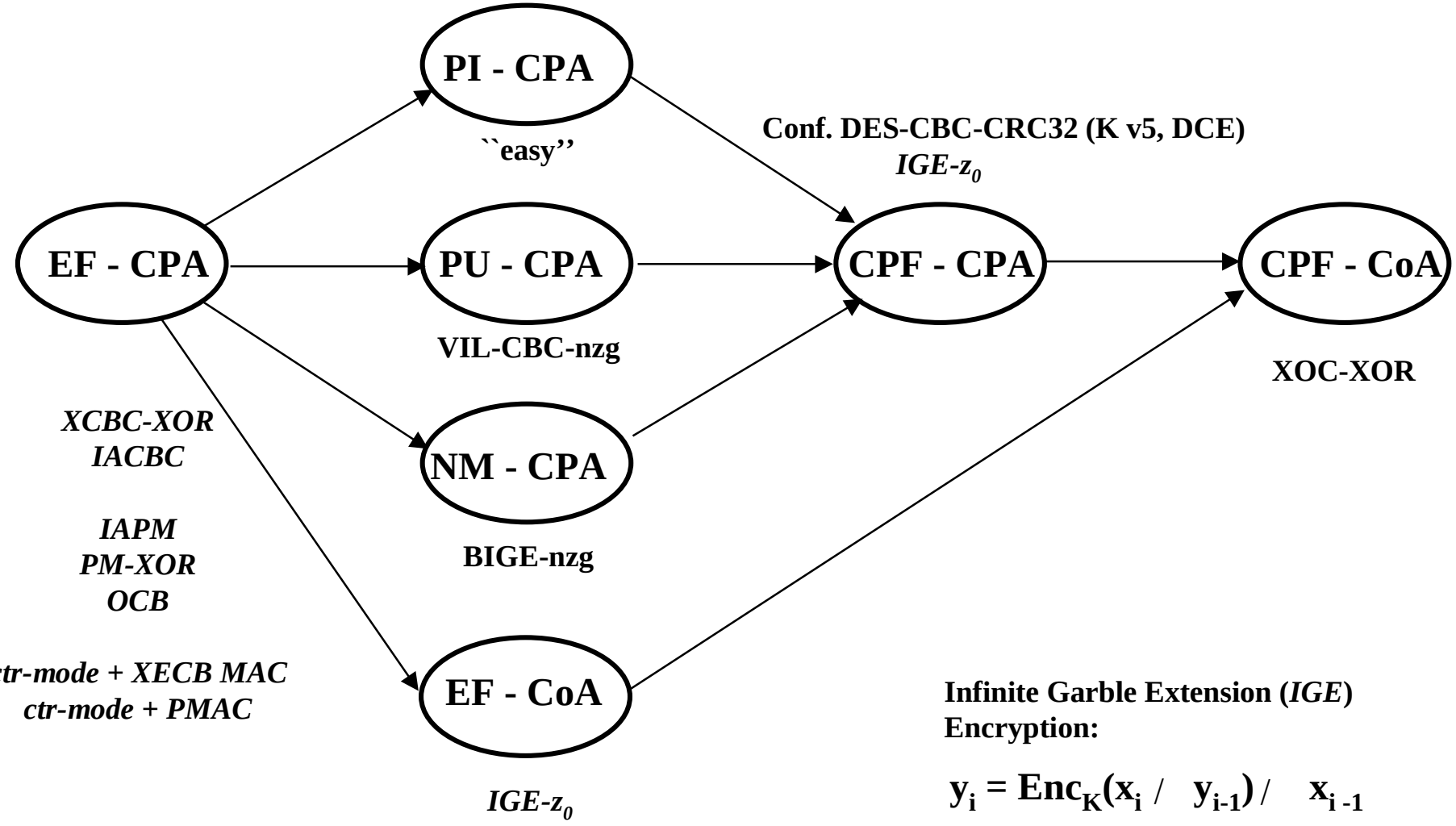
Legend: $A \longrightarrow$ **B iff A ==> B and B =/=> A (``dominance'')**

A ==> B iff mode is secure in A is also secure in B

B =/=> A iff mode is secure in B is not secure in A

Examples of Modes Satisfying Different Integrity Notions

Encryption Mode - "redundancy" function *or* Encryption Mode + MAC Mode



Note: italics designate modes presented in NIST Workshop on AES Modes of Encryption

2. Operational Claims for Modes of Encryption

1. ***Claim*** = a operational notion supported by a mode or scheme of encryption
2. Operational ***Notion*** = < operational goals, mode characteristics >
3. Operational ***Goal***: cost-performance, simplicity, others
    - Examples of (related) goals:
        - cost-performance:
            - low power consumption
            - high speed (e.g., throughput)
            - low implementation cost (e.g., hardware ``real-estate'')
        - simplicity
            - single cryptographic primitive, key
4. ***Mode Characteristics***
    - Examples:
        - State: stateless, stateful
        - Degree of parallelism
            - sequential
            - interleaved (apriori known or negotiated no. of proc. units)
            - fully parallel (independent of no. of processing units)
        - Separated Confidentiality and Integrity keys
        - Other: incremental, out-of-order processing

Examples of Operational Claims

Low- and High-End Goals

• cost-performance:	
• low power consumption	
• speed: moderate (e.g., < 100 MBS)	> 100 GBS
• low implementation cost	hardware
• simplicity	
• single cryptographic primitive (AES), key	single crypto prim.

Low- and High-End Mode Characteristics

• State: stateful	stateful, stateless
• Degree of parallelism	
• sequential (single processor)	fully parallel for Conf. & Integrity
• Separated Confidentiality and Integrity keys: No	Yes
• Others: incremental, out-of-order processing: No	Yes for both Conf. & Integrity

3. Evidence for Claims

1. Mode specification

2. Security Claim

- **goal - attack pair(s)**

3. "Proof "

- **formal: Mode spec. satisfies Security Claim**
  - **standing assumption: AES is secure w.r.t. all known attacks**
- **peer review**
- **other empirical evidence: known attacks**

4. Operational Claim

- **goal - mode characteristics pair(s)**

5. Operational evidence

- **implementation + performance tests**
- **other empirical evidence**

XCBC Encryption

Fact: Encryption is not intended to provide integrity

Motivation

- Encryption w/o integrity checking is all but useless [Bellovin 98]

- Define family of encryption modes to help provide integrity with non-cryptographic "redundancy" functions

- Security claims: IND-CPA confidentiality and EF-CPA integrity, reasonable bounds

- Operational claims: preferred for Low- to Mid-End op. environment

- Knowledge of operational environments:

- **apriori obtained**
- **discovered via negotiation**

Operational Claims

Preferred environments : low- to mid-end

Goals

- cost performance

- low power consumption
- speed: moderate to high (e.g., close to CBC-UMAC-MMX30)
- low implementation cost

- simplicity

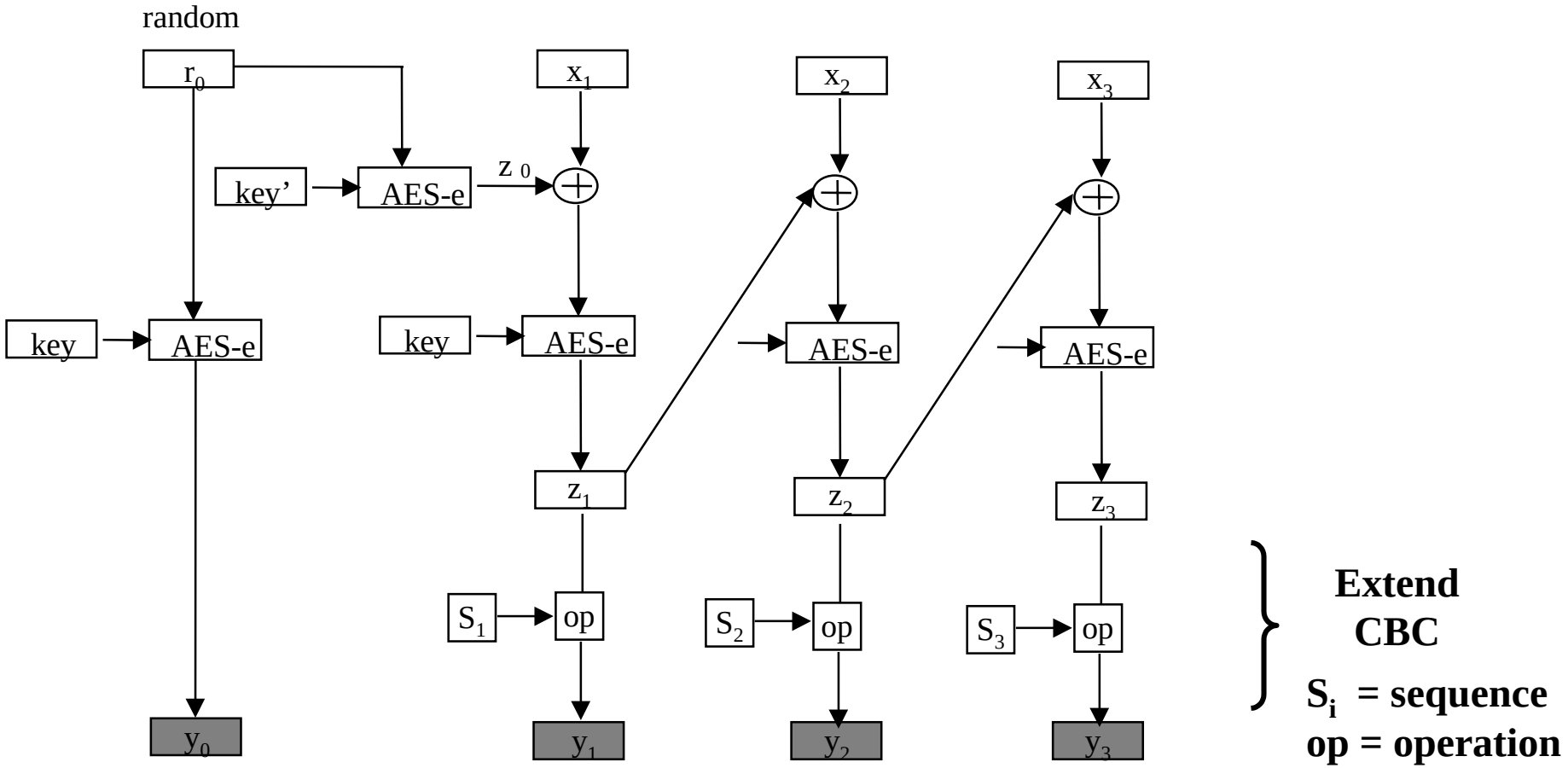
- single cryptographic primitive (AES), key

Mode Characteristics

- State: stateful, stateless
- Degree of parallelism: sequential (single processor), interleaved (known no. procs.)
- Separated Confidentiality and Integrity keys: No
- Others: incremental, out-of-order processing: Yes (if interleaved)

Stateless XCBC Scheme - Encryption of $x = x_1x_2x_3$

(single key is also possible)

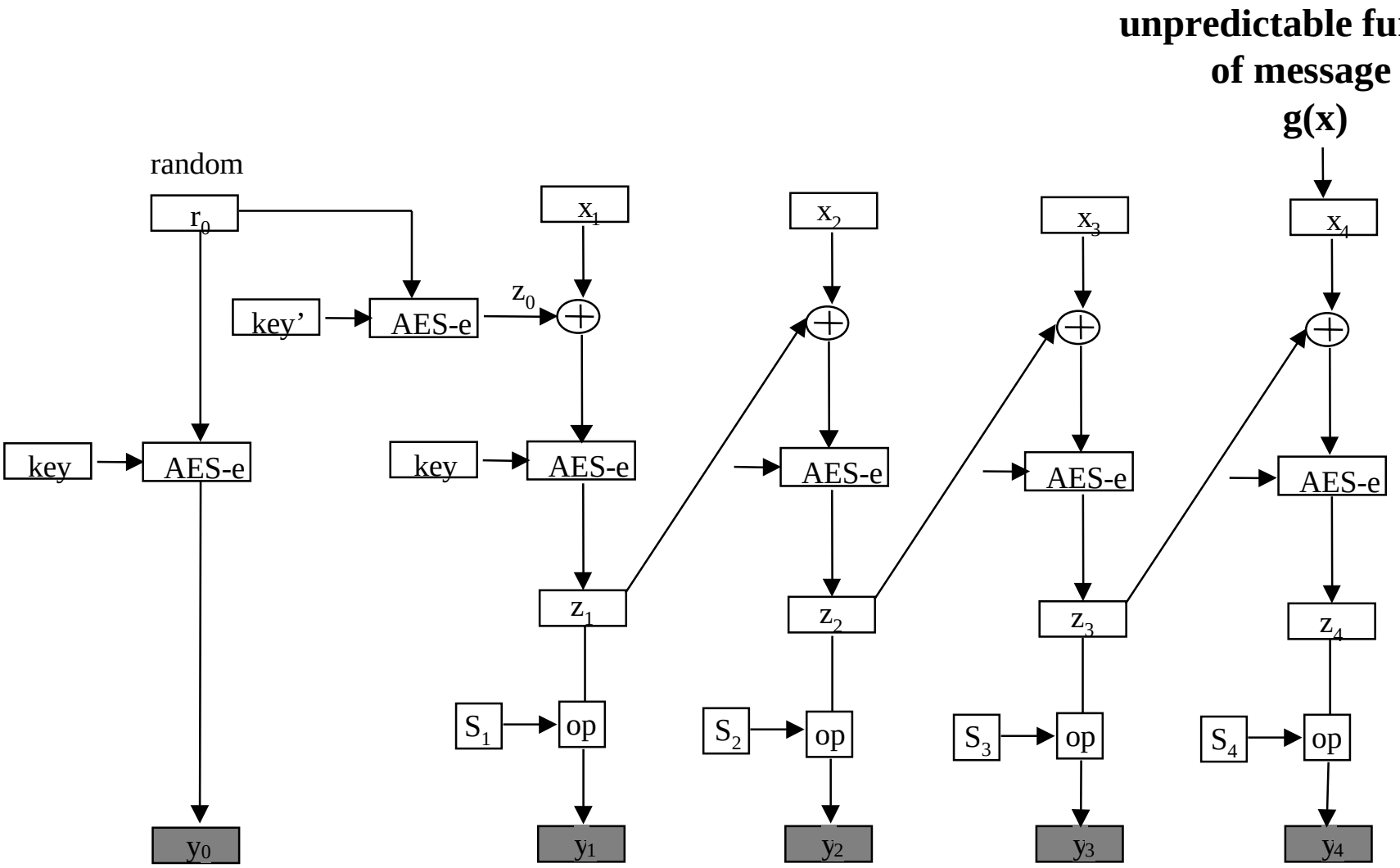


Examples of S_i and *op* combinations (+ is mod 2^l; $\oplus$ is bitwise exclusive-or)

op = + $S_i = S_{i-1} + r_0$, $S_0 = 0$ **(written as** $S_i = i \times r_0$**)**

Other S_i and *op* definitions exist (e.g., C.S. Jutla's and P. Rogaway's proposals)

Stateless XCBC-XOR Scheme - Encryption of $x = x_1x_2x_3$



Example: $g(x) = x_1 \oplus x2 \oplus x3 \oplus z'_0$; $z'_0 = z_0$

Other examples of g(x) exist

Selection Criteria for S_i, op, g(x) ?

Satisfy Security Claims:

- Proof for integrity goal: EF-CPA

(*must be able to do the proofs for selected S_i, op, g(x)*):

• integrity: [GD 00]

Satisfy Operational Claims:

- Goals: low- to mid-end environments

Performance Example (by Jason S. Papadopoulos)

PC: 366 MHz Intel Celeron; OS: Red Hat Linux 5.2;
Compiler: egcs; optimization: -o3-mcpu = I686 - fomit - frame - pointer
Block Enc/Dec : openSSL DES

in-cache timing : 64B, 256B, 512B, 1KB, 2KB, 4KB, 8KB, 16KB, 64KB, 256 KB

- aligned data on 8 byte boundary

CBC-UMAC-MMX30	**42.86 - 46.48 clocks / byte; and for 8B - 77.23 clocks/byte**
XCBC-XOR	**43.38 - 44.62 clocks / byte; and for 8B - 49.57 clocks/byte**

- unaligned data (8 byte boundary +1)

CBC-UMAC-MMX30	**44.13 - 47.35 clocks / byte; and for 8B - 80.85 clocks/byte**
XCBC-XOR	**44.38 - 45.00 clocks / byte; and for 8B - 49.58 clocks/byte**

XECB - MAC

Motivation

- Stand-alone, fully parallel family of MACs, like the XOR-MAC
- **with better throughput**
- **reasonable security bounds for EF- CPA**

- XORC (and ctr-mode) needs a MAC with similar mode characteristics using the same cryptographic primitive

[XORC, and ctr-mode, does *not* allow non-cryptographic "redundancy" function g(x)]

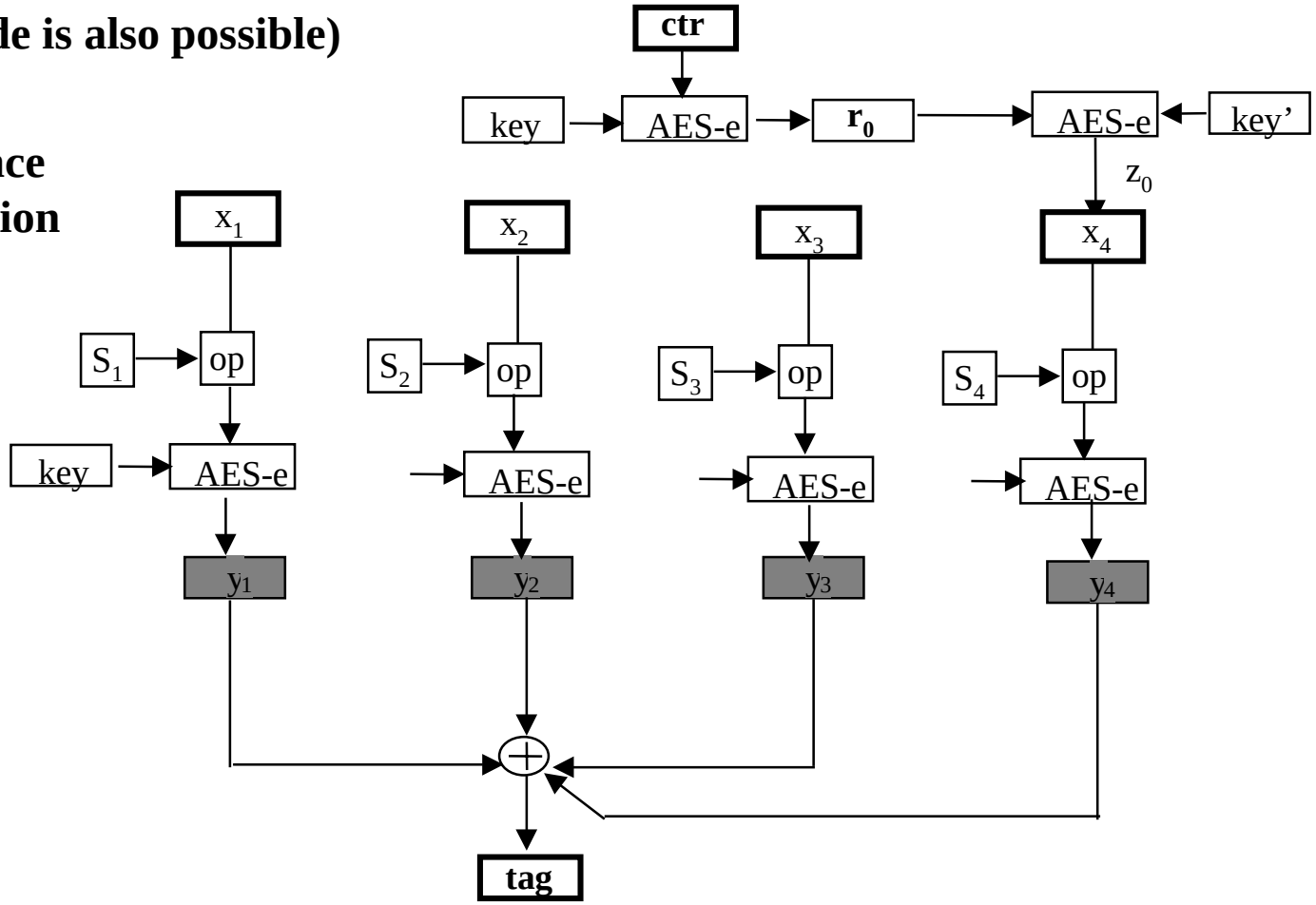
Preferred Operational Environment: High-End

- XORC (ctr-mode) + XECB (or any other similar MAC) requires two keys
=> two separate passes in *single processor, sequential* implementations
=> approx. twice the power consumption and half speed of XCBC-XOR

Stateful XECB - MAC: Example $x = x_1x_2x_3$

(single key mode is also possible)

S_i = sequence
op = operation



Examples of S_i and *op* combinations (+ is mod 2^l; $\oplus$ is bitwise exclusive-or)

op = + $S_i = S_{i-1} + r_0$, $S_0 = 0$ **(written as** $S_i = i \times r_0$**)**

op = $\oplus$ $S_i = S_{i-1} \times a$, $S_0 = r_0$ **(written as** $S_i = a^i \times r_0$ **; *a* is a *lcs* constant)**

Other S_i and *op* definitions exist (e.g., P. Rogaway's PMAC)

Parallel Mode

Motivation

- Fully Parallel Mode like C.S. Jutla's IAPM using a different S_i
(S_i elements are *not* pairwise independent)

- Define family of parallel encryption modes to help provide integrity with non-cryptographic "redundancy" functions

- Security Claims (w/o proof) : IND-CPA confidentiality and EF-CPA integrity, reasonable bounds

Preferred Operational Environment: Mid- to High-End

- Single key for both Confidentiality and Integrity

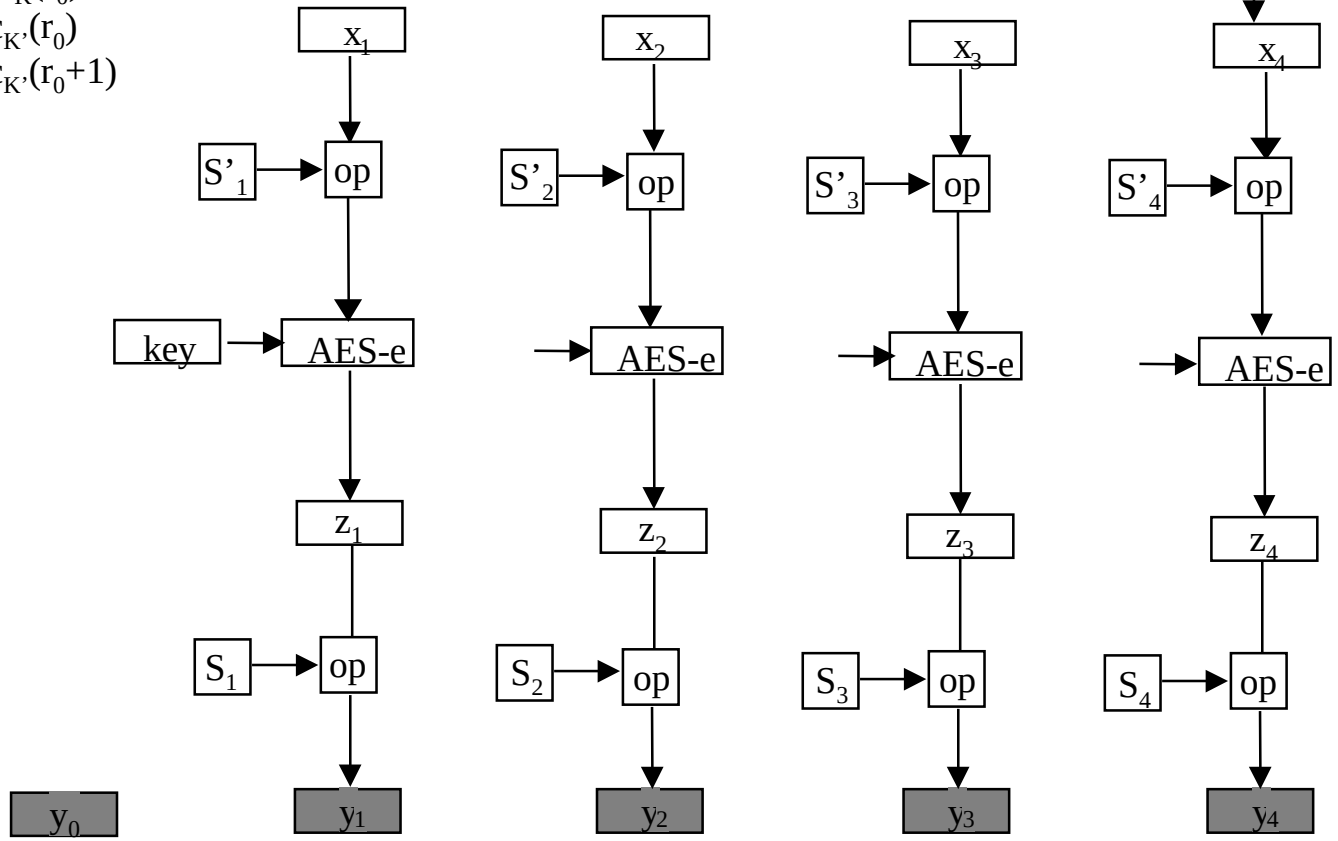
Stateless Parallel Mode - Encryption of $x = x_1x_2x_3$

(single key mode is also possible)

unpredictable function of message x

g(x)

r_0= random;
$y_0 = Enc_K(r_0)$
$z_0 = Enc_{K'}(r_0)$
$z_1 = Enc_{K'}(r_0+1)$



Example: $g(x) = x_1 \oplus x2 \oplus x3 \oplus z_0$;

$y_i = Enc_K(x_i + S'_i) + S_i$; $S'_i = i \times z_1$, $S_i = i \times r_0$; also use DESX if necessary

Other examples of S'_i, S_i, g(x) exist (e.g., C.S. Jutla's and P. Rogaway's proposals)

Proposal: Three* Distinct Modes of Operation

and Candidates (as of 10-18-2000)

- **based on *preferred* environments of operation**

1. ***Low- to Mid-End (very simple extensions of the venerable CBC)***

- **XCBC-XOR**
- **(possibly) interleaved mode**
- **IACBC**
- **XIGE-z_0 / XABC -z_0 (XCBC-like extensions of IGE / ABC)**

2. ***Mid- to High-End (single confidentiality and integrity key)***

- **IAPM**
- **PM-XOR**
- **OCB**

3. ***High-End (separate or independent key for confidentiality and integrity modes)***

- **ctr-mode for encryption**
- **XECB-MAC, PMAC for integrity**
- **(*) ctr-mode + XECB-MAC, ctr-mode + PMAC for both**

(*) the third mode of operation requires two separate AES modes

Intellectual Property Status

3 patent applications filed

Patent Application 1: on 1/31/2000

Patent Application 2: on 3/31/2000

Patent Application 3: on 8/24/2000