A Public-Key Infrastructure for Key Distribution in TinyOS Based on Elliptic Curve Cryptography

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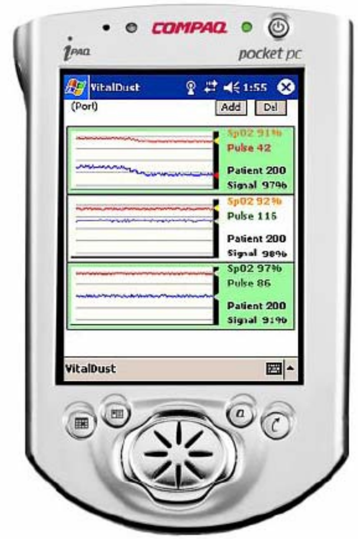
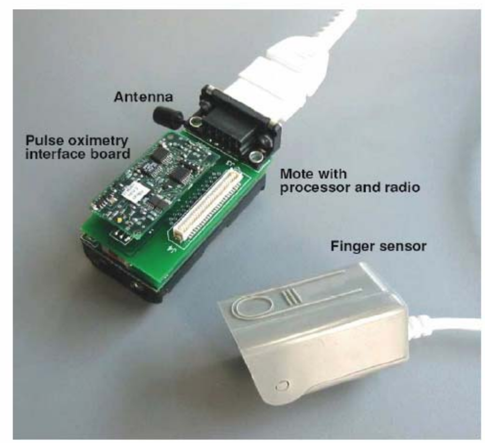
Source Code
http://www.eecs.harvard.edu/~malan/research/

CodeBlue

An *Ad Hoc* Sensor Network Infrastructure for Emergency Medical Care

- Mass casualty incidents (MCIs) involve multiple patients
- Manual tracking of patient status is difficult
  - Current systems are paper-, phone-, and radio-based
- Sensor nets (*e.g.*, mote-based pulse oximeters, EKGs) have potential for large impact
  - Real-time, continuous monitoring
  - Immediate alerts of changes in patient status
  - Electronic triage tags to store patient data
  - Relay data to hospital, correlate with patient records
- Transmission of patient data must be secure (HIPAA)





Ensuring Privacy and Security

Secret-Key Cryptography

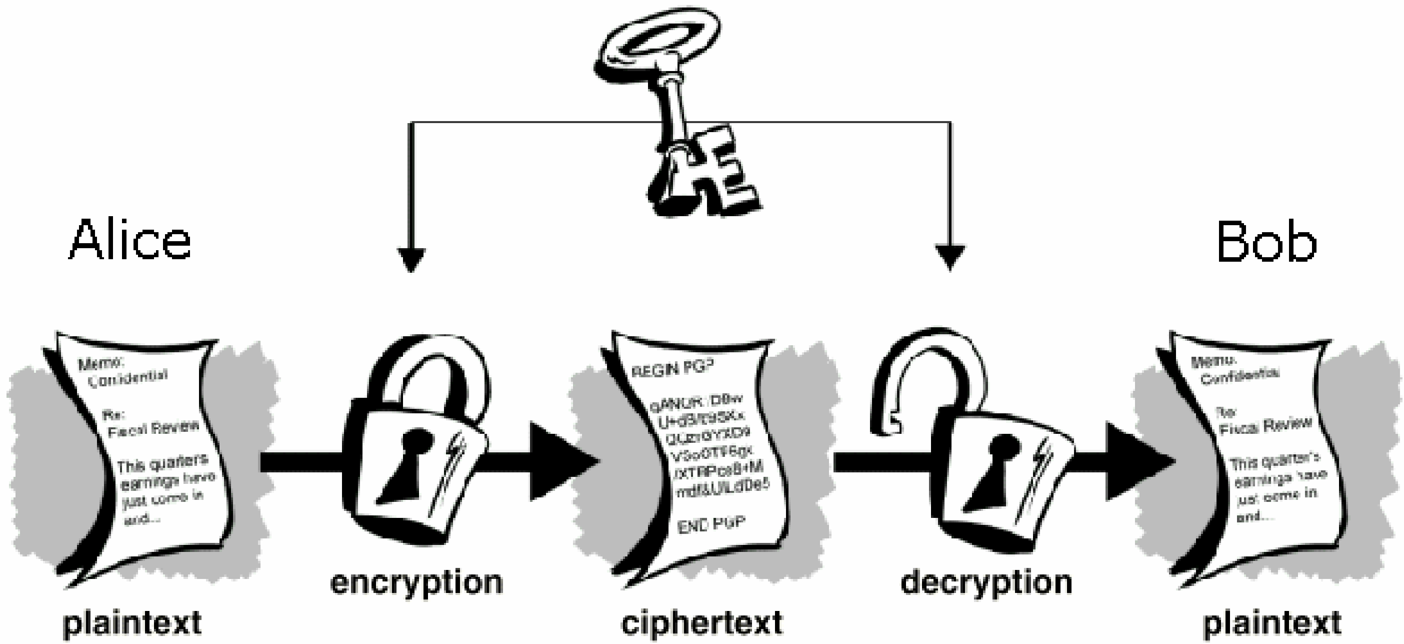
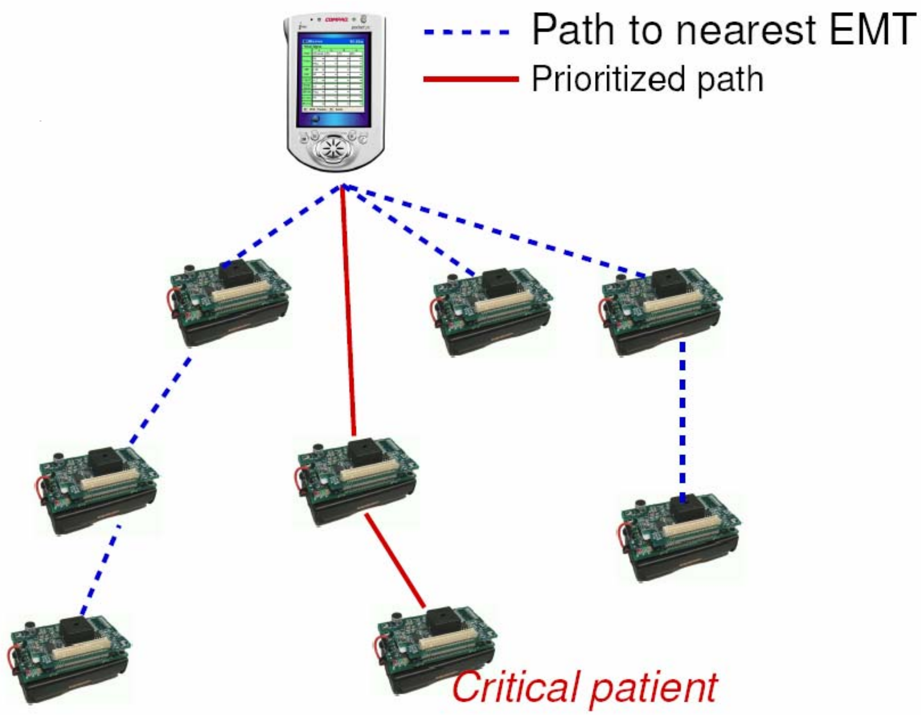


Image adapted from `http://www.nuitari.de/crypto.html`.

Ensuring Privacy and Security

The Problem: Key Distribution

- How to establish shared secrets among authorized nodes?
  - Network participants are coming and going
  - Motes themselves are vulnerable to theft



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A Solution: Public Key Infrastructure (PKI)

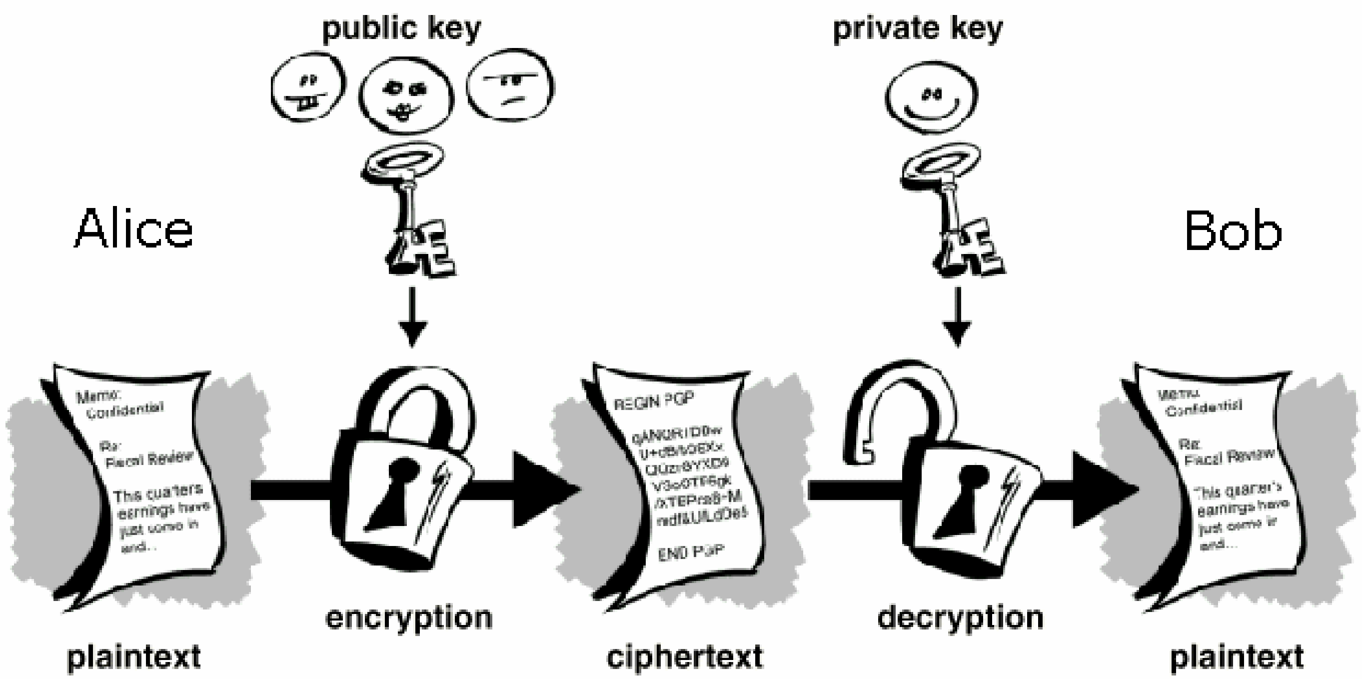


Image adapted from `http://www.nuitari.de/crypto.html`.

Ensuring Privacy and Security

The Real Problem: Implementation of PKI on Motes

- “Public key cryptography is prohibitively expensive for sensor networks in terms of computation and energy consumption.”
  - C. Karlof, N. Sastry, and D. Wagner, “TinySec: Link Layer Security for Tiny Devices,” `http://www.cs.berkeley.edu/ nks/tinysec/`
- “Many current sensor devices have limited computational power, making public-key cryptographic primitives too expensive in terms of system overhead.”
  - A. Perrig, J. Stankovic, and D. Wagner, “Security in Wireless Sensor Networks,” *Communications of the ACM*, vol. 47, no. 6, pp. 53–57, June 2004

Ensuring Privacy and Security

Context for This Problem

- The MICA2 Mote
  - Developed at UC Berkeley
  - Fabricated by Crossbow, Inc.
  - Supported by TinyOS, UC Berkeley's open-source operating system for sensor networks
  - Limited Resources
    - 8-bit, 7.3828-MHz ATmega 128L processor
    - 4 KB of primary memory (SRAM)
    - 128 KB of program space (ROM)
    - 512 KB of EEPROM
    - 433-MHz radio: 38.4K baud rate, 29B per-packet payload

Image exerpted from http://www.xbow.com/Products/Product_pdf_files/Wireless_pdf/6020-0042-05_A_MICA2.pdf.

Our Goals

Is PKI, in fact, viable for key distribution on the MICA2?

1. Analysis of UC Berkeley's TinySec, TinyOS's existing secret-key infrastructure for the MICA2 based on SKIPJACK with 80-bit keys
2. Evaluation of BBN Technologies' implementation of Diffie-Hellman with 1,024-bit keys (*i.e.*, 160-bit exponents and 1,024-bit moduli), per NIST's recommendation
3. Evaluation of our own implementations of elliptic curve cryptography (ECC) with 163-bit keys, per NIST's recommendation

Spoiler Ahead!

PKI is, in fact, viable for key distribution on the MICA2

1. SKIPJACK with 80-bit keys
   - Fast
   - Negligible impact on radio throughput
2. Diffie-Hellman with 1,024-bit keys
   - Relatively slow
   - Key sizes unappealing
3. ECC with 163-bit keys
   - Promising performance
   - Key sizes appealing

SKIPJACK and the MICA2

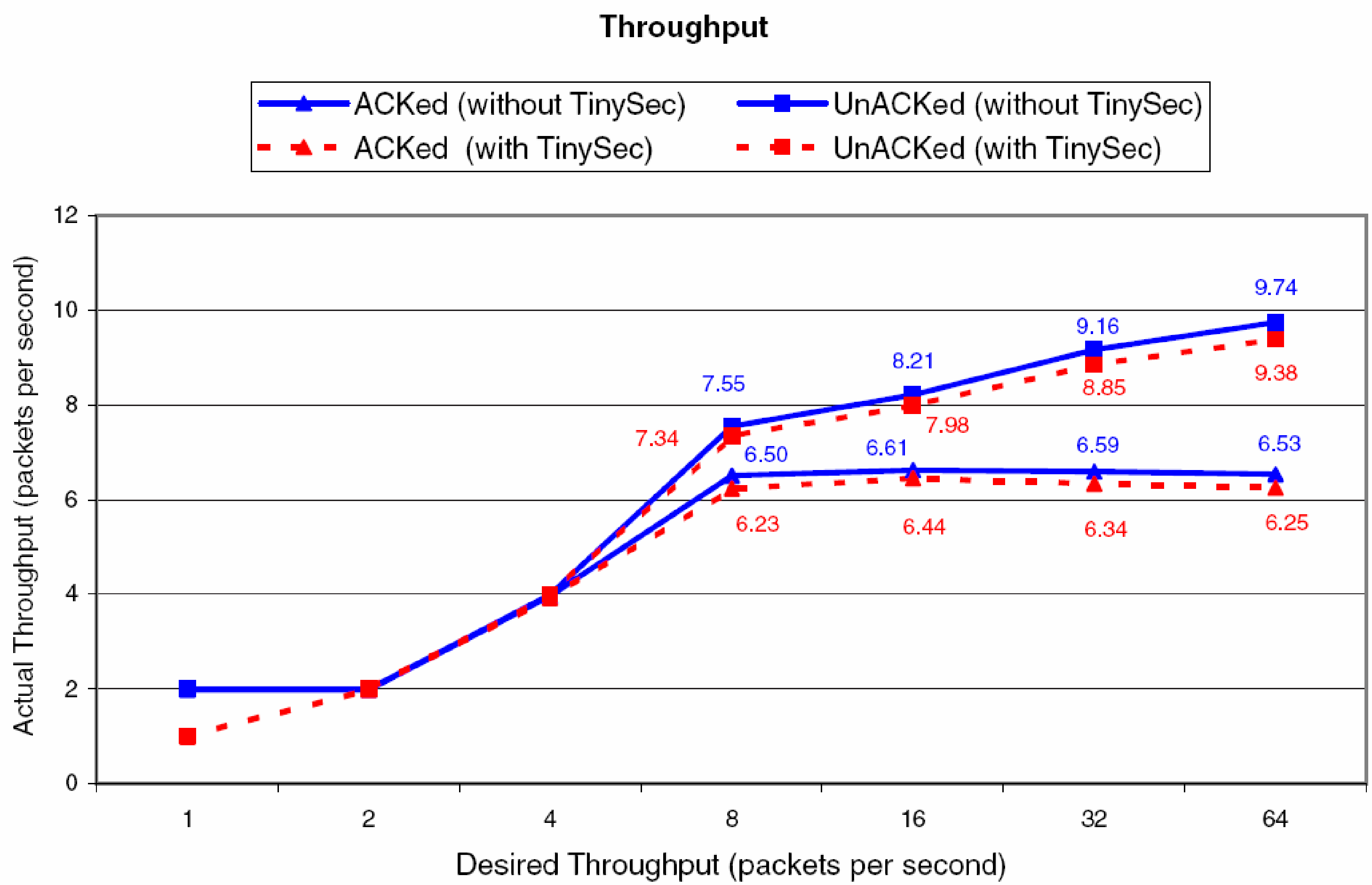
Costs are reasonable

- Costs in time
  - **`encrypt()`**
    - 2,190 μsec
  - **`computeMAC()`**
    - 3,049 μsec
- Costs in space
  - 822 B of SRAM
  - 7,076 B of ROM

See paper for breakdown of SRAM into `.bss`, `.data`, and stack requirements.

SKIPJACK and the MICA2

Impact on Throughput Is Negligible



Diffie-Hellman and the MICA2

A Typical Exchange (determining x given g^x mod p is hard)

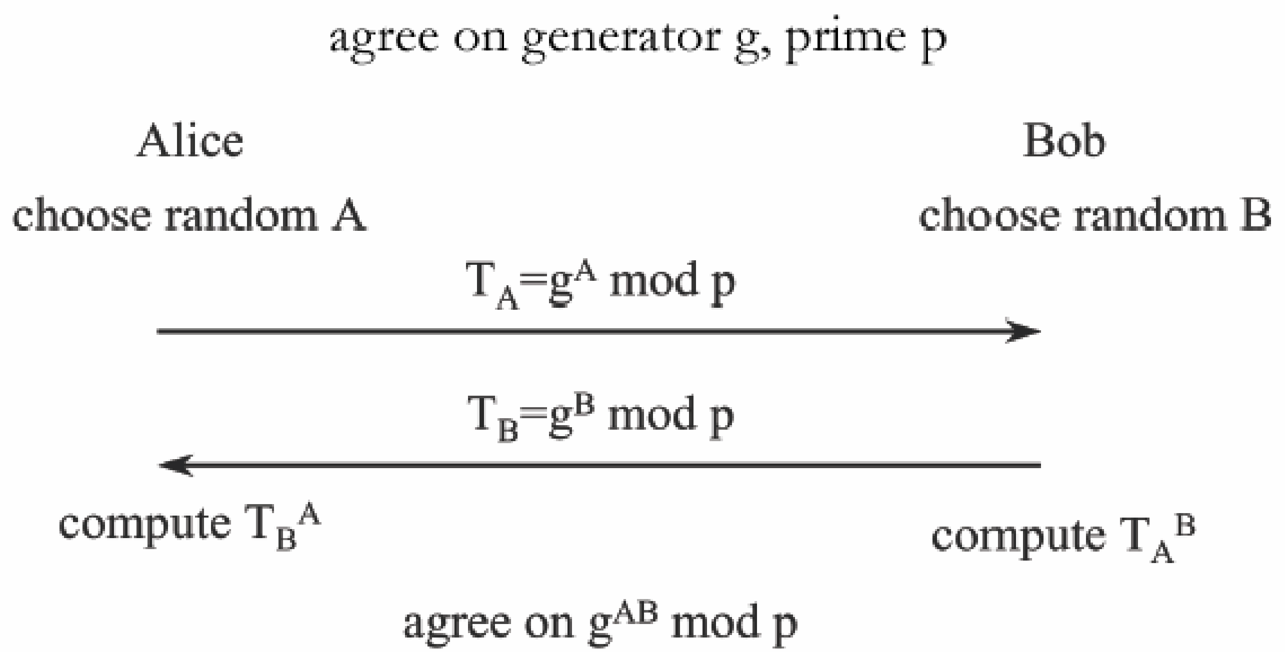
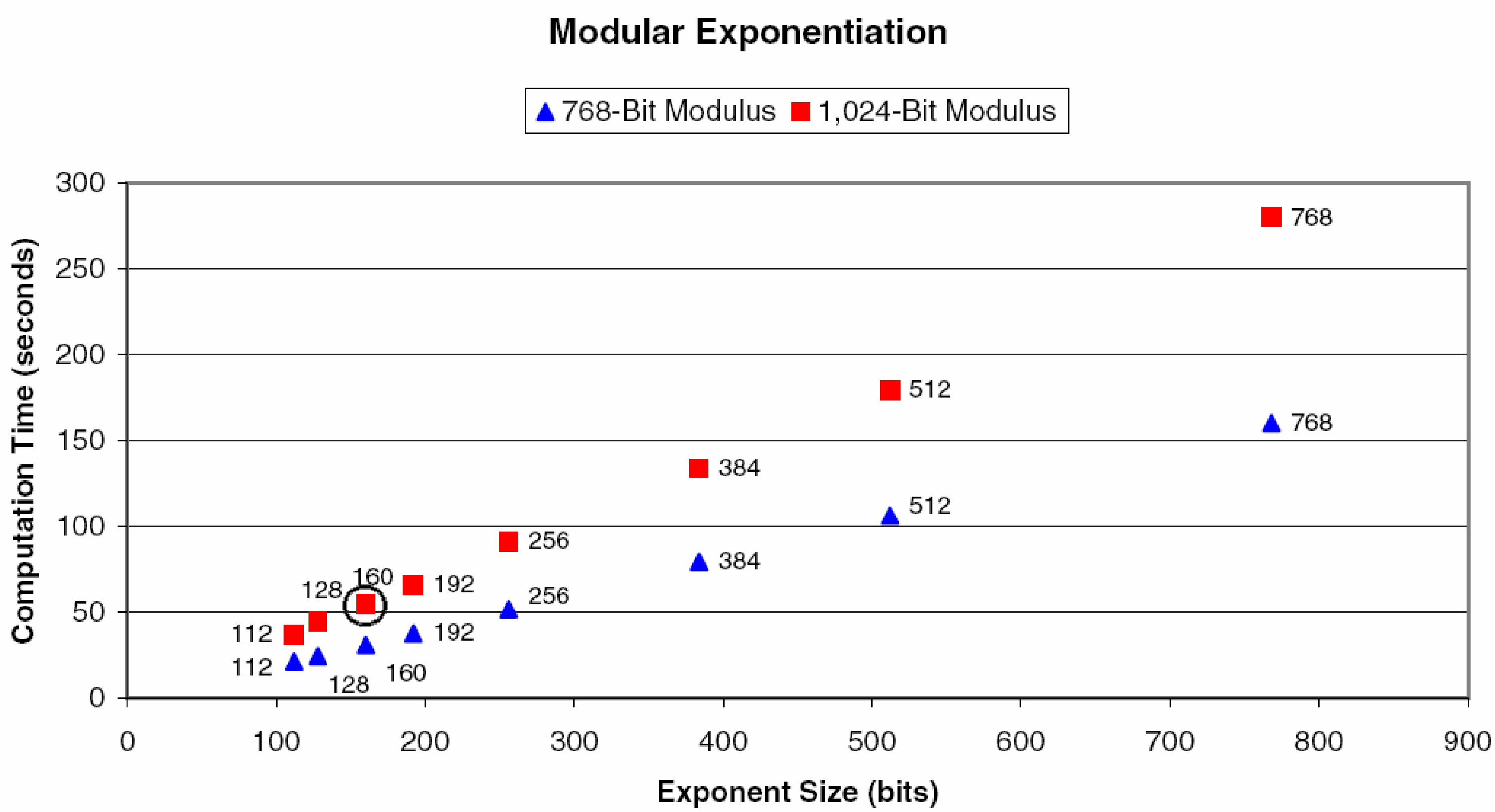


Image adapted from Radia Perlman's Computer Science 243.

Diffie-Hellman and the MICA2

Performance Is Relative Slow



Time required to compute $2^x \pmod{p}$, where p is prime, on the MICA2.

Diffie-Hellman and the MICA2

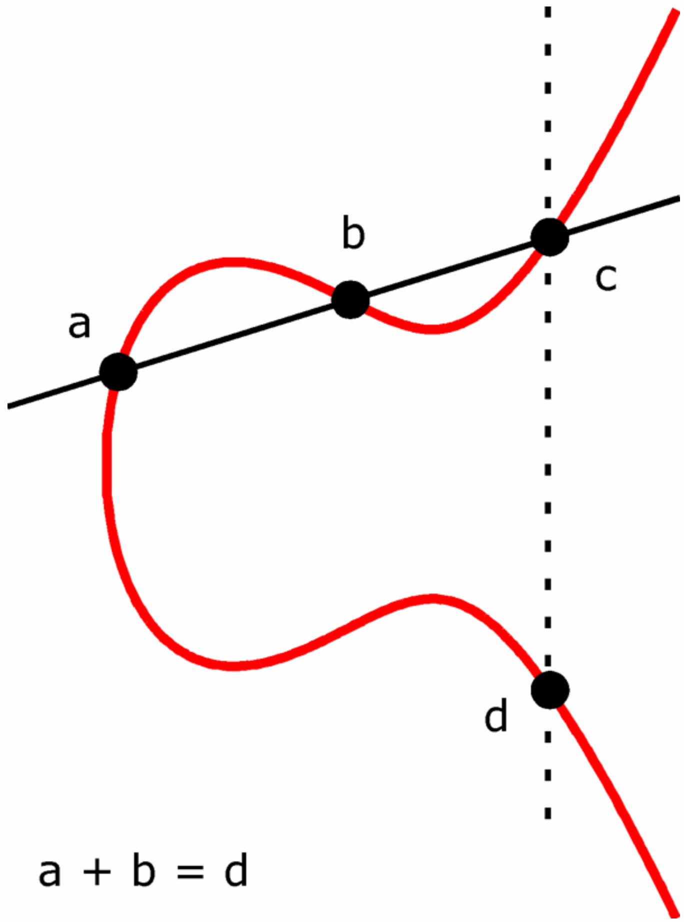
Costs of Generating a 1,024-Bit Public or Shared Key Are Significant

- Cost in time
  - 54.1144 sec
- Costs in space
  - 1,250 B of SRAM
  - 11,350 B of ROM
- Cost in energy
  - 1.185 Joules (3.9897 x 10^8 cycles)

See paper for breakdown of SRAM into `.bss`, `.data`, and stack requirements.

ECC and the MICA2

An Elliptic Curve, over Real Numbers



ECC and the MICA2

A Typical Exchange (determining k_x given k_x * G is hard)

point G is publicly known

Alice		Bob
choose random k_A		choose random k_B
	$T_A = k_A * G$ →	
	← $T_B = k_B * G$	
compute $k_A * T_B$		compute $k_B * T_A$

agree on $k_A * k_B * G$

ECC and the MICA2

Our Elliptic Curve, over GF(2^{163}) Using a Polynomial Basis

curve

$$y^2 + xy \equiv x^3 + x^2 + 1$$

order

0x4000000000000000000020108a2e0cc0d99f8a5ef

point $G = (G_x, G_y)$

$$\begin{aligned} G_x &= \text{0x2fe13c0537bbc11acaa07d793de4e6d5e5c94eee8} \\ G_y &= \text{0x289070fb05d38ff58321f2e800536d538ccdaa3d9} \end{aligned}$$

reduction polynomial

$$f(x) = x^{163} + x^7 + x^6 + x^3 + 1$$

ECC Offers Better Performance *and* Smaller Keys (163 v. 1,024 bits)

Costs of Generating a 163-Bit Public or Shared Key Are Lower

- Cost in time
  - 34.161 sec
- Costs in space
  - 1,140 B of SRAM
  - 34,342 B of ROM
- Cost in energy
  - 0.816 Joules (2.512 x 10^8 cycles)

See paper for breakdown of SRAM into `.bss`, `.data`, and stack requirements.

Optimizations

Our Two Implementations of ECC (EccM 1.0 and EccM 2.0)

- Our first implementation of ECC, a straightforward port of Michael Rosing's code in *Implementing Elliptic Curve Cryptography*, proved a failure
- Our current implementation reflects the design of Dragongate Technologies' Java-based jBorZoi and employs various optimizations
  - Source-level, hand optimizations (*e.g.*, manually unrolled loops, special cases for common shifts)
  - Published algorithms from current literature (*e.g.*, J. López and R. Dahab, "High-Speed Software Multiplication in F_{2^m}," Institute of Computing, Sate University of Campinas, São Paulo, Brazil, Tech. Rep., May 2000)

Related Work

Current Literature

- C. Karlof, N. Sastry, and D. Wagner, “TinySec: A Link Layer Security Architecture for Wireless Sensor Networks.” Second ACM Conference on Embedded Networked Sensor Systems, November 2004
- N. Gura, A. Patel, A. Wander, H. Eberle, and S. C. Shantz, “Comparing Elliptic Curve Cryptography and RSA on 8-bit CPUs.” 6th International Workshop on Cryptographic Hardware and Embedded Systems, August 2004
  - 0.81 sec for 160-bit point multiplication over GF(p)

Future Work

Considerations for EccM 3.0

- GF(p)
- Normal Basis
- AVR Assembly

Conclusion

PKI is, in fact, viable for key distribution on the MICA2

1. SKIPJACK with 80-bit keys
   - 2,190 µsec for `encrypt()`
   - 3,049 µsec for `computeMac()`
2. Diffie-Hellman with 1,024-bit keys
   - 54.1144 sec for key generation
   - 1,250 B of SRAM
   - 11,350 B of ROM
   - 1.185 Joules (3.9897 x 10^8 cycles)
3. ECC with 163-bit keys
   - 34.390 sec for key generation
   - 1,140 B of SRAM
   - 34,342 B of ROM
   - 0.82149 J (2.5289 x 10^8 cycles)

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