Challenges: Communication through Silence in Wireless Sensor Networks

Yujie Zhu and Raghupathy Sivakumar
GNAN Research Group
Georgia Institute of Technology

Energy Based Transmission (EbT)

- Traditional communication strategy that conveys information
- between the sender and the receiver using energy only

- Procedure:
  - Sender interprets the information to be transmitted as a bit stream
  - Sender transmits the bit stream
  - Receiver receives the bit stream
  - Information delivered!

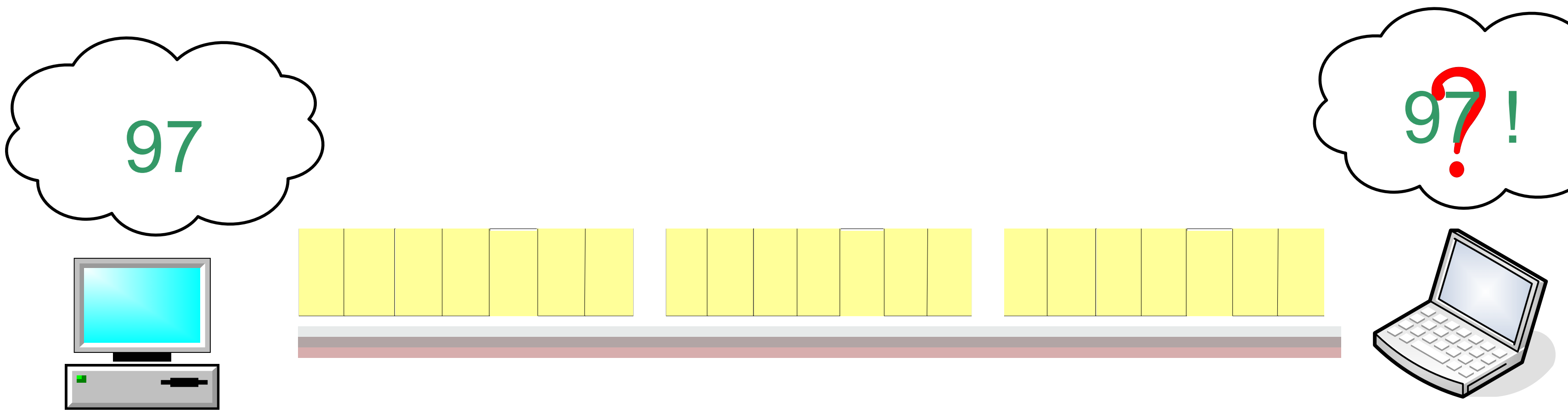
- The energy consumption for EbT is k*eb* where k is the length of
- the bit stream and eb is the amount of energy used to transmit
- one bit

- Example:
- It takes 20eb for EbT to send a raw data packet of 20 bits without
- considering the overhead

Georgia Institute of Technology

GNAN Research Group

Energy Based Transmission (EbT)



Georgia Institute of Technology

GNAN Research Group

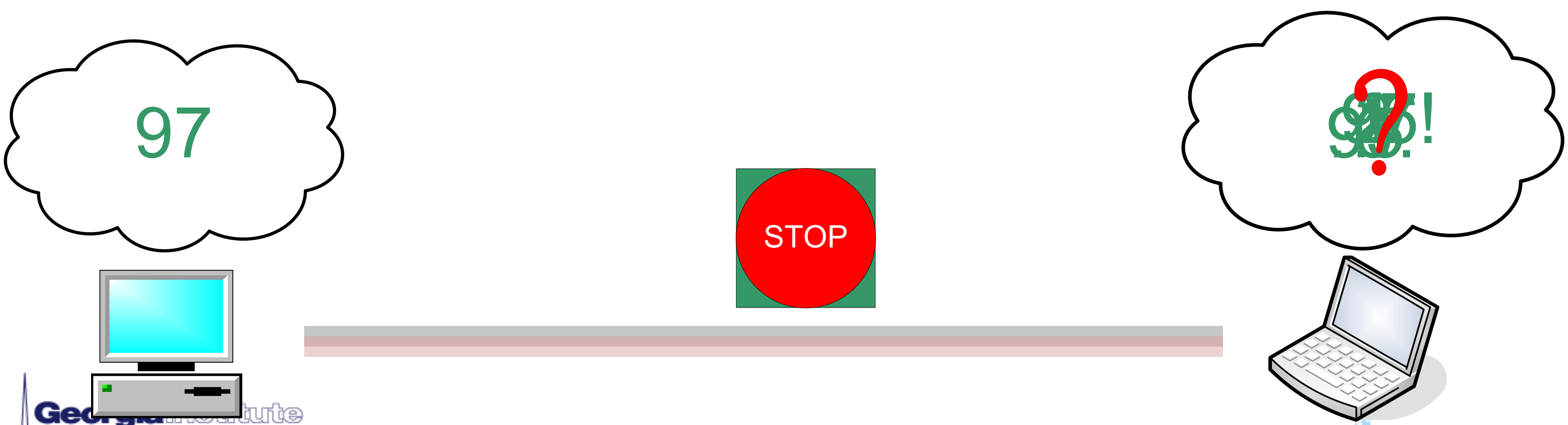
Communication through Silence (CtS)

- A new communication strategy that conveys information using silent perio ds in tandem with small amount of energy
- Procedure:
  - Sender interprets the information to be transmitted as a data value
  - Sender transmits start signal
  - Receiver starts to count from 0 upon receiving start signal
  - Sender and receiver are synchronized in counting clock
  - Sender transmits stop signal when receiver counts up to the desired
  - value
  - Information delivered!
- The energy consumption for CtS is always 2*eb* irrespective of the
- value being sent.
- Example:
- It takes 2eb for CtS to send a raw data packet of 20 bits without
- considering the overhead
- → 10X improvement in energy consumption!

Georgia Institute of Technology

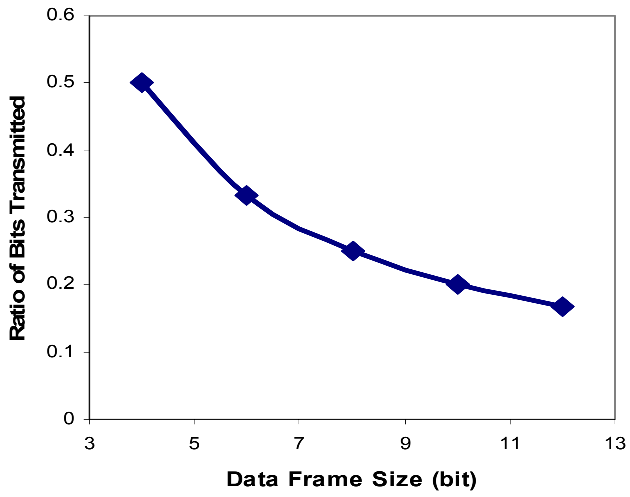
GNAN Research Group

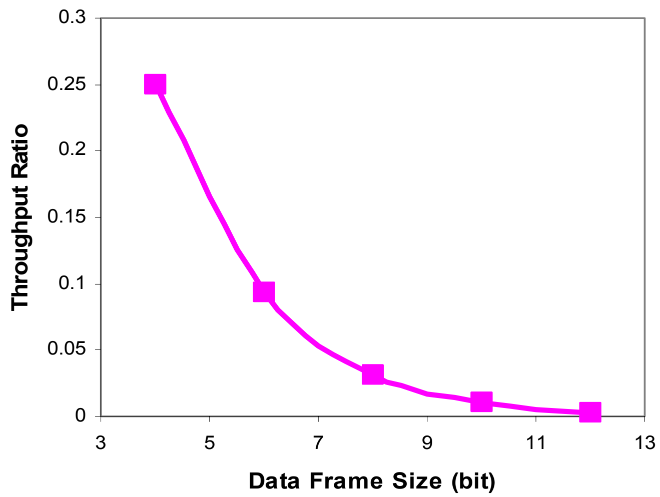
Communication through Silence (CtS)



Energy - Throughput Tradeoff

The CtS strategy incurs exponential throughput decrease compared to EbT





The energy consumed for transmitting each bit of data decreases inverse linearly with data frame size

The time taken to transmit a packet of s bits is 2^s using Cts

→ The throughput of CtS decreases as $s/2^s$

Example:10Mbps data rate, 10 bit data frame size

Energy improvement: 5 times

Effective throughput: 10Kbps

Georgia Institute of Technology

GNAN Research Group

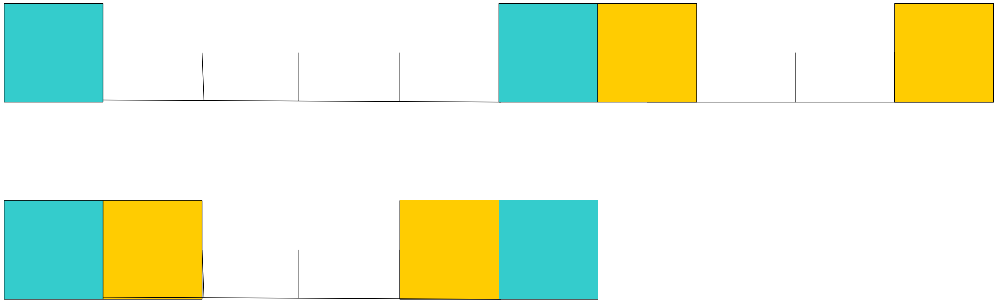
Optimization Strategies Overview

- Exploit the unique characteristics of CtS to improve upon the considerably low throughput performance of basic CtS.

- Assumptions:
  - ✓ The start and stop signals are uniquely addressable
  - ✓ Each start/stop signals occupies one bit
  - ✓ The communication channel is lossless
  - ✓ The sender and the receiver clocks are perfectly synchronized
  - ✓ There are no counting errors

Multiplexing

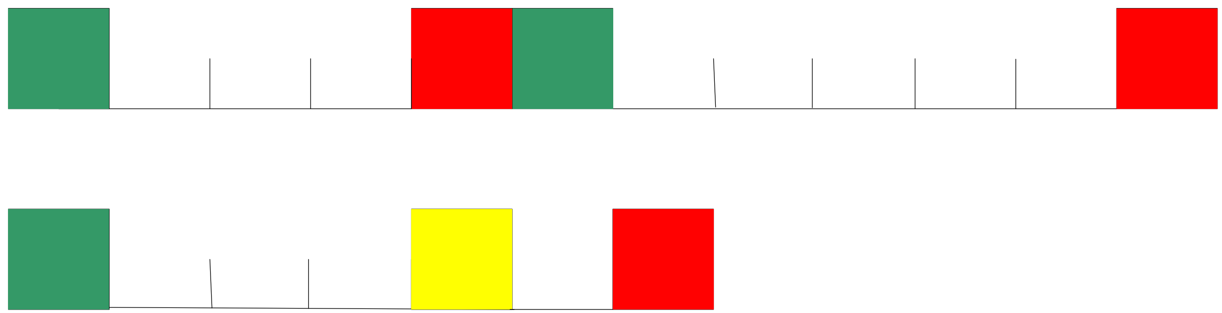
- Two or more contending sender-receiver pairs can transmit at the same time as along as the start/stop signals do not overlap



- Enabled by the typical long silent intervals between start and stop signals in CtS
- Not possible in EbT since a sender-receiver pair has to occupy the channel exclusively during transmissions

Cascading

- Consecutive data values that are monotonically increasing or decreasing can be sent in a combined “signal train” consist of one start signal, multiple intermediate signals and one stop signal instead of multiple consecutive start/stop signals



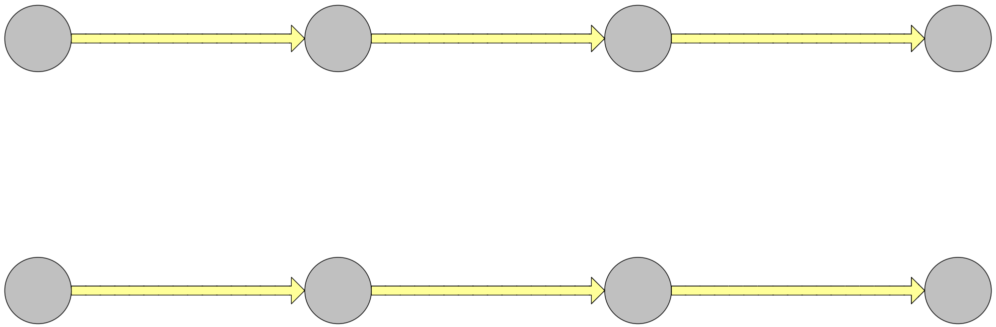
- The same counting process can be used for multiple packets at the same time for CtS
- Not possible in EbT since overlapped data packets confuse the receiver

Georgia Institute of Technology

GNAN Research Group

Fast-forwarding

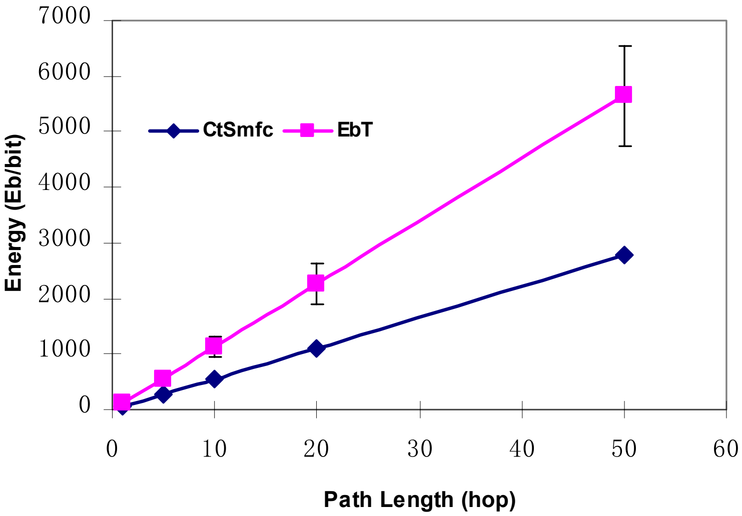
- For multihop CtS communication, a relay node can forward start/ intermediate signals before the stop signal is received

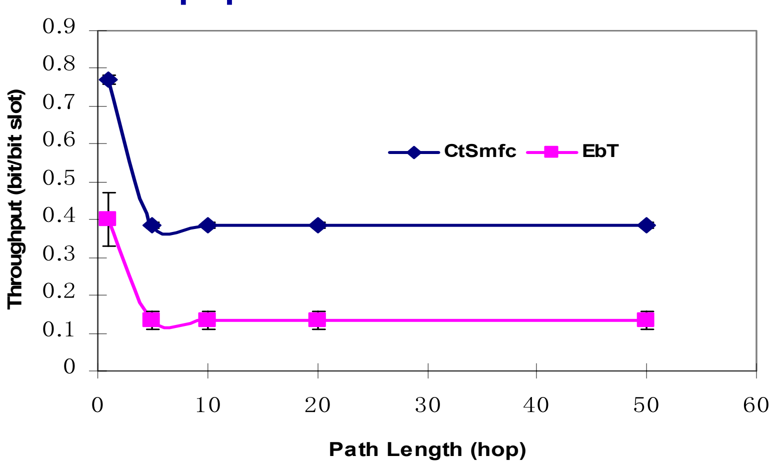


- Enabled by the separable signals of each packet and possibility of simultaneous counting in CtS
- Not possible in EbT because a packet has to be received in full before forwarding to ensure content integrity

Integrated Operation

- A multi-hop sensor network
- Sink located at the center of the network
- Average degree = 10
- A randomly chosen sensor sends data to sink via an *h*-hop path





- The throughput of integrated CtS is up to twice that of EbT
- The energy consumption of EbT increases faster with path length than integrated CtS

Summary of Benefits

Summary:

- The energy-delay trade-off of basic CtS strategy can be alleviated by
  - Proper combination of optimization strategies
  - Adaptation of parameters

Georgia Institute of Technology

GNAN Research Group

Challenges Overview

Appropriate protocols tailored to the CtS paradigm from the physical layer to MAC layer, and possibly higher layers

PHY layer requirements:

Synchronization overhead for carrier based transmission → Baseband modulation

Limited energy supply and low transciever complexity → Impulse radio

Addresses embedded in start/stop signals → Pulse train technology

Challenge: Framing (1)

- Determining the length of the messages the transmitter will send to the receiver

- The length of the CtS frame determines the amount of delay taken for the transfer of that information.

- Issues:
  - Energy throughput tradeoff
    - Should be small enough such that the delay required for transmission is not prohibitive:
      e.g. A CtS packet size of 100 bytes incurs delay as high as 2^{800} bit slots!
    - Should be large enough to ensure acceptable energy saving

  - Contention Resolution
    - Large frame size reduces the chances of collisions when simple contention resolution mechanisms are employed

Challenge: Framing (2)

- A simple solution:
  - Set the CtS delay frame size to be 256-65536 bit slot, which translates to a CtS data frame size of 8-16 bits, based on empirical evaluation
  - Translates into 10Kbps (4X energy improvement) and 100bps (8X energy improvement) respectively for a 10Mbps raw data rate network.

- Drawbacks of this solution:
  - The optimal frame size is yet to be determined within the given range
  - Need an adaptive scheme to vary the frame size according to network conditions

Challenge: Addressing (1)

- Identify the sender and the intended receiver in a CtS frame

- For a shared media, a node needs to know if the received packet is for itself, and where this packet comes from
- Given the limited CtS frame size, embedding the sender and receiver ID in the frame will be too much an overhead

- Issues:
  - How to identify the sender and receiver in an efficient way
  - How to reduce the addressing overhead

Challenge: Addressing (2)

- A simple solution:
  - Local addressing scheme
    - Record the original global source and destination addresses only in the "regular" link layer frame handled by CtS
    - In the CtS frames, locally computed addresses that distinguish only between sensors in a neighborhood will be encoded
    - Minimum coloring problem
  - Modulate signals with the address information
    - Impulse radio
    - Pulse train
    - Translate the code into pulse-shift or phase shift pattern

- Drawbacks:
  - Global coordination is required to find the minimum coloring number
  - Update of local IDs may be needed to accommodate network dynamics

Challenges: Sequencing

- Providing a way for the receiver to determine the order of CtS frames received

- Enable the receiver to reconstruct higher layer frames in the presence of CtS frames reordering

- Issues:
  - Sequence number results in significant overhead in CtS frames

- A Simple solution:
  - Deliver all the CtS frames belonging to the same higher layer frame back to back: → no sequence number required!

- Drawbacks:
  - Introduce extra delay when CtS frame is being retransmitted
  - Any completeness check can be performed only after the arrival of all CtS frames

Challenge: Error Control (1)

- Preventing errors in the delivery of CtS frames
- Detecting errors and/or recover from errors in CtS frames

- Retransmission of CtS frames aggravate the already low CtS throughput

- Issues
  - Correctness of CtS requires:
    - Precise delivery of the start/stop/intermediate signals
    - Perfect synchronization of sender-receiver counting clocks
  - Traditional error control techniques may not be applicable
    - Applying error control coding to each CtS frame incurs high overhead

Challenge: Error Control (2)

- A Simple solution:
  - Rely solely on error control only at the granularity of the “regular” link layer frames

- Drawbacks:
  - One erroneous CtS frame causes the corruption and retransmission of the entire higher layer frame
  - Extra coding may be required to identify the erroneous CtS frame in a higher link layer frame

Challenge: Contention Resolution (1)

- Resolve contentions when the communication channel is shared by multiple CtS senders and receivers

- Traditional contention resolution schemes can be highly resource intensive for CtS

- Issues
  - Only need to avoid overlapping of start/stop signals
  - Approaches such as carrier-sensing are not applicable due to the short duration of signals transmitted
  - Exchange of control packets for contention resolution causes high overhead

Challenge: Contention Resolution (2)

- A simple solution: ALOHA scheme
  - Inherent low channel access probability of CtS
  - ALOHA works best when the network load is less than 20%
  - Collisions of start/stop signals can be detected by error control scheme and trigger retransmission
- Drawbacks:
  - Not adaptive to network load
  - Relies on error control strategies to detect errors

Other challenges

- Design effective PHY layer solutions tailored to CtS MAC layer strategies and specific application environments

- Design effective routing layer solutions that reduce control packet overhead and leverage the characteristics of CtS

- Other brand new solutions may be needed for CtS:
  - Topology control
  - Synchronization
  - Sleep scheduling
  - Adaptive transmission strategies
  - And more ..

Related work & Conclusions

- Related work
  - Timing channel
    - Used for covert communication
    - Intervals between data packets are interpreted as codes in an alphabet
    - Not optimized for energy and throughput
  - Digital Pulse Interval Modulation
    - A modulation scheme
    - Use intervals between pulses to encode information
    - Typical frame length is 3-5 bits

- Conclusions
  - Introduced the new paradigm of *Communication through Silence* for wireless sensor networks
  - Identified the energy-throughput trade-off of CtS
  - Presented unique optimization strategies to improve upon the throughput performance of CtS
  - Discussed several research challenges related to the realization of CtS

Thanks!

Questions & Comments ?