CSCE 438/838: Internet of Things

Exam 2

- Friday, Dec. 2^{nd}, in class at 9:30am
- Coverage: Communication, MAC, Error Control, Localization, Synchronization
- Open book/notes, everything allowed except for digital media (laptop, phone, tablet, etc)
- Sample questions will be posted on Canvas

Project Milestone 1

- Customer Requirements
- Engineering Requirements
- Test

Customer Requirements

- What does the customer expect?
  - List of functions or services expected
  - Constraints on the system (e.g., cost, given equipment)
  - Success criteria
- Enumerated (C1, C2, …) for easy reference across papers
- Have the customer sign off

Engineering Requirements

- What are the software/hardware functionalities to meet expectations?
  - List of functions by the hardware/software at a greater detail
  - Performance criteria (speed, size, reliability, cost, safety, security)
- Each customer requirement should lead to one or more engineering requirements (E1, E2, …)
- List should be complete such that it can act as the only list of requirements

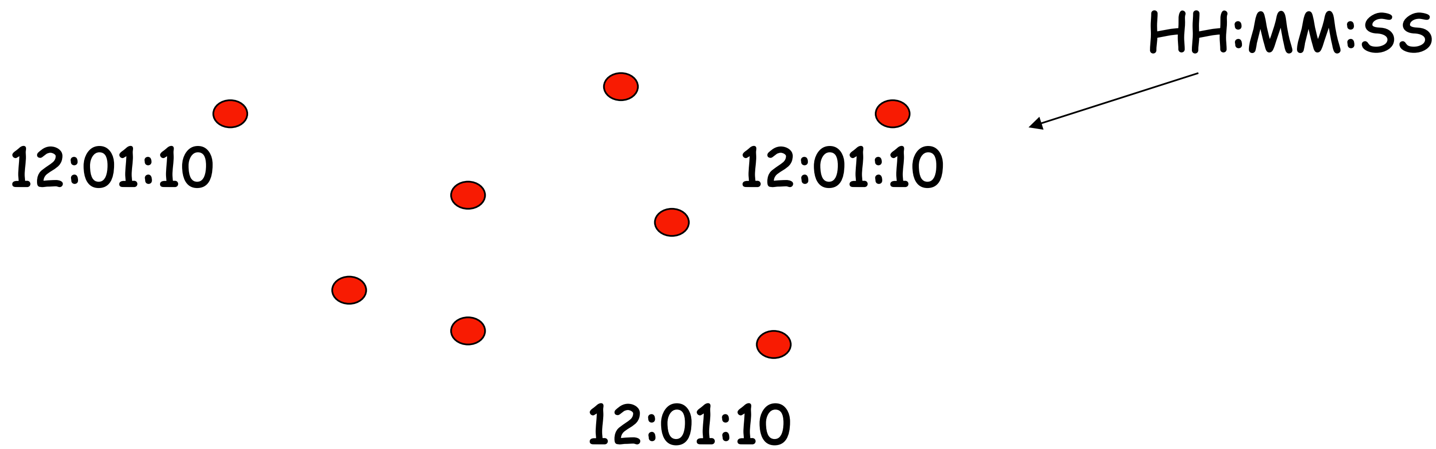
Test Plan

- How do we know the system really works?
  - List of tests (spreadsheet)
  - List of test results (date, setup, number of trials, passed, failed, not yet run)
  - Records of peer review results
- Test every requirement (engineering & customer)

Time Synchronization

Time Synchronization

What is time synchronization in IoT?



Objective: Allow all sensor nodes to maintain the same time frame

Time Synchronization

- Temporal relations play an important role in sensor fusion → Which event happened first?

- Physical time is itself part of information
  - Estimation of target position: Direction, Speed
  - Providing fire breaking time

- Due to the clock drift, the local clock needs to be periodically synchronized to maintain an accurate global time

Time Synchronization Challenges

- Why is it so difficult to synchronize the sensor nodes?
- Low-end timers (i.e., clock crystals) are used
  - Clock drifting may be significant and clock jitters may occur often
- Communication links are noisy
  - Some sensor nodes may become unsynchronized
- Node failures occur often
  - Cannot depend on a single sensor node to be the master clock

Timer

- Timer: A counter that is updated based on a clock signal
  - Timer = Counter + Clock
- Clock: A periodic signal with a certain frequency (clock freq.)
  - A single period is called a tick
- Any timer holds the number of ticks at the clock frequency, since a particular instance in time
- ES Clock ≠ Wall clock
- ES Timer ≠ Wall clock (except RTC)

Clock

- CPU needs a clock source
- MCU spends most of its time in a low-power mode
- Need precise clock source to wake up at certain (real) times
- Need a clock source for time stamping
- High frequency (HF) clock: Can be started and stopped rapidly, need not be very accurate
- Low frequency (LF) clock: Run continuously to track real time, low power, accurate

Clock Oscillators

- Two common types
- Crystal: Accurate (the frequency typically within 1 part in 10^5) and stable (does not change greatly with time or temperature)
  - Typically run at either a high frequency of a few MHz or a low frequency of 32,768 Hz for a real-time clock.
  - Expensive and delicate
  - Draws a large current
  - Takes a long time to start up and stabilize
  - Requires external components (e.g., capacitor)
- Resistor and capacitor (RC): Cheap and quick to start but used to have poor accuracy and stability.
  - Integrated within the MCU
  - Recent MCUs provide accuracy to within ±1%

Crystal

- https://www.youtube.com/watch?v=1pM6uD8nePo

Factors Influencing Time Synchronization

Factors Influencing Time Synchronization

- Temperature
  - Temperature variations during day may cause the clock speed up or down (a few μsec/day).
- Phase Noise
  - Access fluctuation at the hardware interface, response variation of the operating system to interrupts, jitter in delay, etc.
- Frequency Noise
  - The frequency spectrum of a crystal has large sidebands on adjacent frequencies.

Factors Influencing Time Synchronization

- Asymmetric Delay
  - The delay of a communication path may be different for each direction
- Clock Glitches
  - Hardware or software anomalies may cause sudden jumps in time

Sources of Time Synchronization Error

- Sending Time (Time spent at the sender to construct the message)
  - Kernel protocol processing
  - Variable delays caused by OS
  - Transfer within the host to radio
- Access Time (Delay caused to wait for access to the channel)
  - Specific to MAC protocol

Sources of Time Synchronization Error

- Propagation Time
  - Can be neglected for air
  - Important for underground, underwater
- Receiving Time
  - Processing required for the antenna to receive the message from the channel and notify the processor of its arrival (A/D conversion)

- Common Denominator: Non-deterministic!!!!

Further Difficulties

- Periodic message exchange is not guaranteed to occur among nodes
- Transmission delay between two nodes is hard to estimate

TERMINOLOGY

- FREQUENCY:
  - The rate at which a clock progresses.
- CLOCK OFFSET/DRIFT:
  - Difference between the time reported by a clock and the real time (or by another clock).
- CLOCK SKEW:
  - Difference in the frequencies of the clock and the perfect clock (or another clock).
- DRIFT (RATE) of a CLOCK:
  - Second derivative of the clock value with respect to time.

Relativity

- Einstein predicted that relativistic effects cause clock drift due to time dilation
- Time Dilation: There is no fixed universal time, time is relative to the observer
- Gravitational time dilation: A clock in a stronger gravitational field will appear to tick more slowly
- It is time, not the clock that drifts!
- Example: GPS satellites
  - GPS clocks run faster than those on Earth
  - Relativistically corrected calculations are needed
  - Without synchronization, navigational fix will be incorrect within 2 minutes
  - Accumulates to 10km error per day

Clock Models

- Time deviation of a clock
- $C_l(t) - t = \underline{\theta_l} + \underline{\gamma_l} t + \underline{\omega_l} t^2 + \underline{\epsilon_l}(t)$

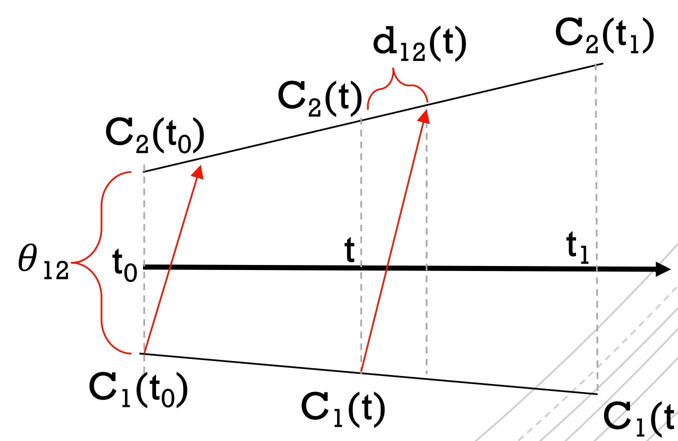
time offset

frequency offset

frequency drift

random variations

- Clock Relation Model
- $C_2(t) = \underline{\alpha_{12}} C_1(t) + \underline{\theta_{12}} + \underline{\epsilon_{12}}(t) + (1+\gamma_2) d_{12}(t)$
- $\alpha_{12} = \frac{1+\gamma_2}{1+\gamma_1}$,
- $\theta_{12} = \theta_2 - \alpha_{12}\theta_1$,
- $\epsilon_{12} = \epsilon_2 - \alpha_{12}\epsilon_1$



Clock Discipline Algorithms

- Goal: Estimate clock relation model
- Then, predict time reports of $C_1(t)$ based on readings of $C_2(t)$
- Clock relation model
  - $y = \mathcal{R}(x)$
  - $x = C_1(t),\ y = C_2(t)$
- First estimate, $\hat{R}^{-1}(y)$
- $\hat{x} = \hat{R}^{-1}(y)$
- Time difference (estimation error)
  - $\epsilon = C_1(t) - \hat{R}^{-1}(C_2(t))$

Clock Discipline Algorithms

- Offset Only Model
  - Clock relation model
  - $R_1(x) = x + \tau_{12}$
  - Clock skew is assumed to be unity and constant
  - $\widehat{R_1}^{-1}(y) = y - \hat{\tau}_{12}$
  - $\hat{\tau}_{12}(t_k) = C_2(t_k) - C_1(t_k)$
  - Has large bias
- Linear Model
  - Clock relation model
  - $R_2(x) = \alpha_{12}x + \tau_{12} + \delta_{12}(t)$
  - Unknowns can be estimated through linear regression
  - $\hat{R}_2^{-1}(y) = (y - \hat{\tau}_{12})/\hat{\alpha}_{12}$

Messaging Error Sources

- Transmitter Delays
  - Message processing; deterministic
  - Frame prep; deterministic
  - Software delay; random
  - Encoding time; deterministic
  - Calibration time; random
  - Access time; random
  - Transmission time; deterministic
- Propagation Delays
  - Propagation time; deterministic

Messaging Error Sources

- Receiver Delays
  - Reception time; deterministic
  - Decoding time; deterministic
  - Byte alignment time; deterministic
  - Interrupt handling time; random

Messaging Schemes

- Two-way Message Exchange
- One-way Message Dissemination
- Receiver-only Synchronization
- Receiver-receiver Synchronization

Messaging Schemes

- Two-way Message Exchange
  - Provide most information on clock parameters
  - Higher energy and computational requirements
- One-way Message Dissemination
  - Smallest number of transmissions
- Receiver-only Synchronization
  - Low resilience against node failures
  - High accuracy
  - Low energy consumption
- Receiver-receiver Synchronization
  - Higher accuracy than one-way
  - Increased energy and computational requirements

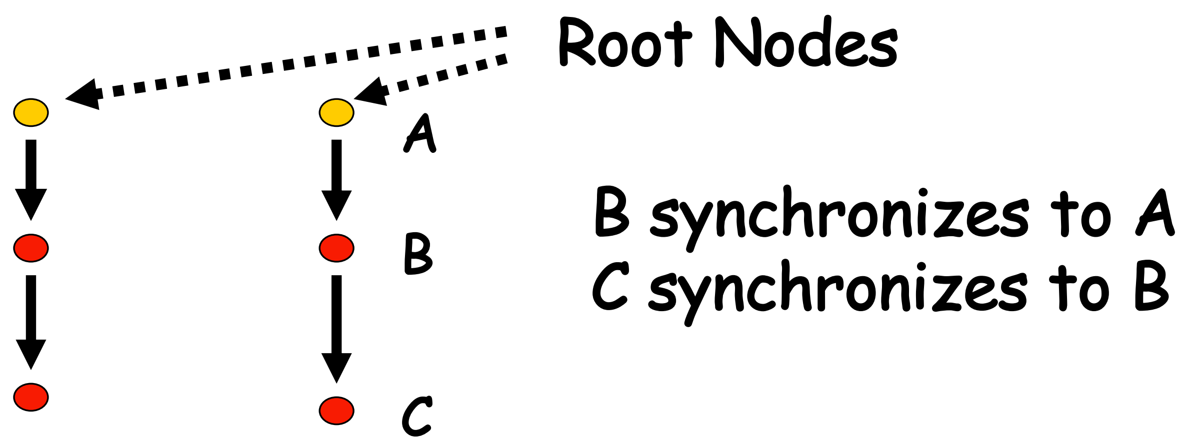
Synchronization Protocol	Messaging Scheme
NTP: Network Time Protocol	Two-way
PTP: Precision Time Protocol	Two-way
TPSN: Time-synchronization Protocol for Sensor Networks	Two-way
RBS: Reference Broadcast Protocol	Receiver-receiver
FTSP: Flooding Time Synchronization Protocol	One-way
FCSA: Flooding with Clock Speed Agreement	One-way
R-Sync: Robust Synchronization	Receiver-only
TDP: Time Diffusion Protocol	Two-way
DTSP: Distributed Time Synchronization Protocol	One-way
GTSP: Gradient Synchronization Protocol	One-way
ATS: Average Time Synchronization	One-way
RFA: Reachback Firefly	One-way
CFO-Synt: CFO-based Syntonization	One-way

Timing-Sync Protocol for Sensor Networks (TPSN)

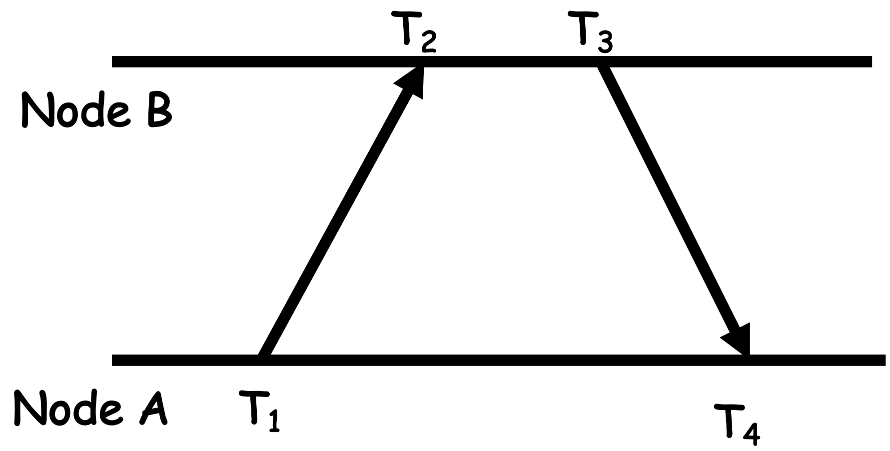
S. Ganeriwal, et.al., "Timing-Sync Protocol for Sensor Networks," ACM SenSys, November 2003.

Features:

- Have many root nodes
- Organize into multiple level hierarchy
- Synchronize level-by-level



TPSN: Time Synchronization



- At time T_1, A sends a sync pulse packet to B, which contains the level number of A and T_1.
- Node B receives this packet at T_2
  - $T_2 = T_1 + D + d$
- D= clock offset between the two nodes
- d= propagation delay
- At time T3, 'B' sends back an acknowledgement packet to 'A' with values of T1, T2, T3 and level # of B.

TPSN: Time Synchronization

- A can calculate the phase (clock) offset D (clock drift) and delay d as

$$D = \frac{(T_2 - T_1) - (T_4 - T_3)}{2}$$

$$d = \frac{(T_2 - T_1) + (T_4 - T_3)}{2}$$

Advantages: TPSN

- Scalable
- Synchronization accuracy does not degrade significantly as the size of the network is increased
- Network-wide synchronization is effectively achieved
- Computationally less expensive

Drawbacks: TPSN

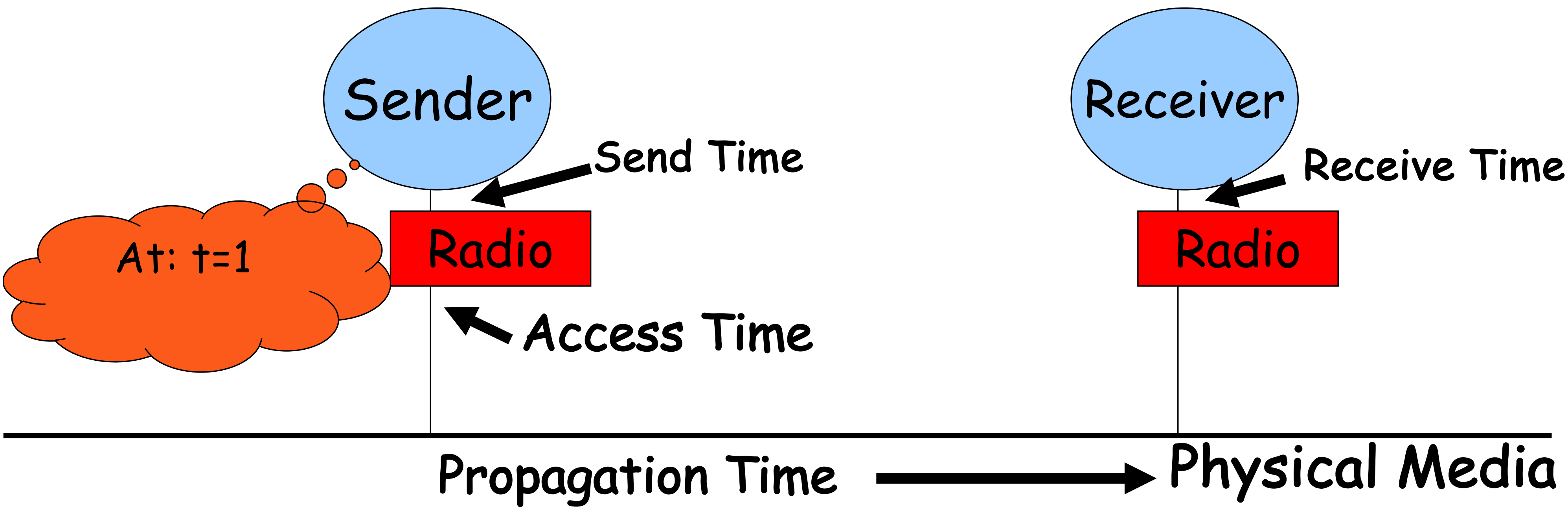
- Energy conservation is not very effective
  - Requires a physical clock correction to be performed on local clocks of sensors while achieving synchronization
- Requires a hierarchical infrastructure
  - Unsuitable for applications with highly mobile nodes
- Support for multi-hop communication is not provided

Drawbacks: TPSN

- Forms islands of time
  - Whole network does not have the same time frame
- Nodes become unsynchronized when mobile
  - All nodes are predefined in a hierarchy.
- No end-to-end common time frame
  - Assumed the end users will be able to interpret the time gathered from the network
- Requires a pre-defined reliable hierarchy of nodes.

Traditional Synchronization

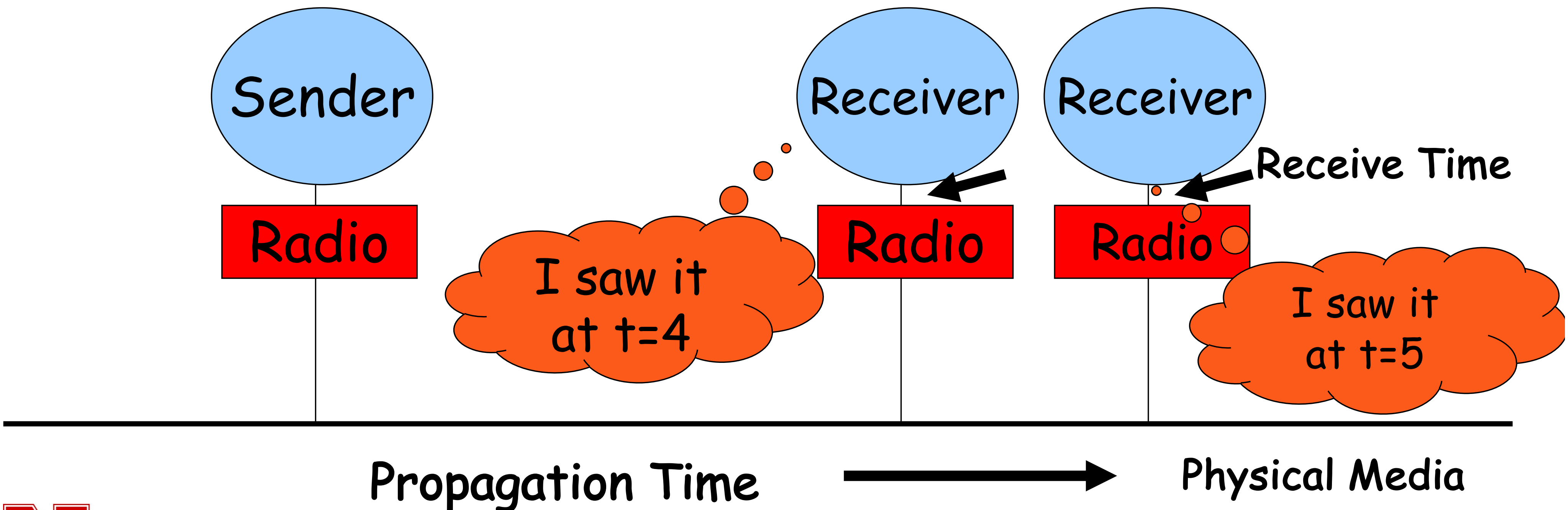
Problem for SYNCH: Many sources of unknown, nondeterministic delays <u>(send time, access time, propagation time and receive time)</u> between sender and receiver



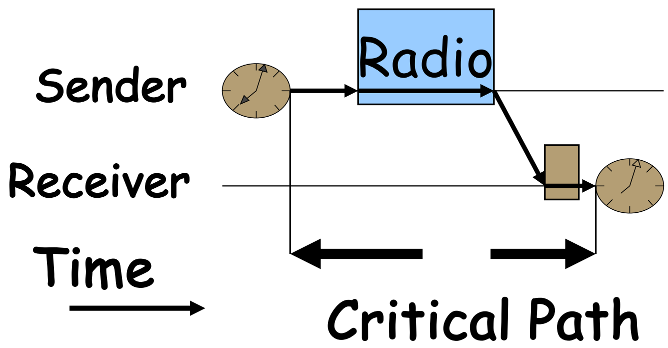
Reference Broadcast Synchronization (RBS)

J. Elson, et. al., “Fine-Grained Network Time Synchronization using Reference Broadcasts,” Proc. of the Fifth Symp. on Operating Systems Design and Implementation (OSDI 2002), Boston, December 2002.

Does not try to sync Sender & Receiver
Tries to sync receivers



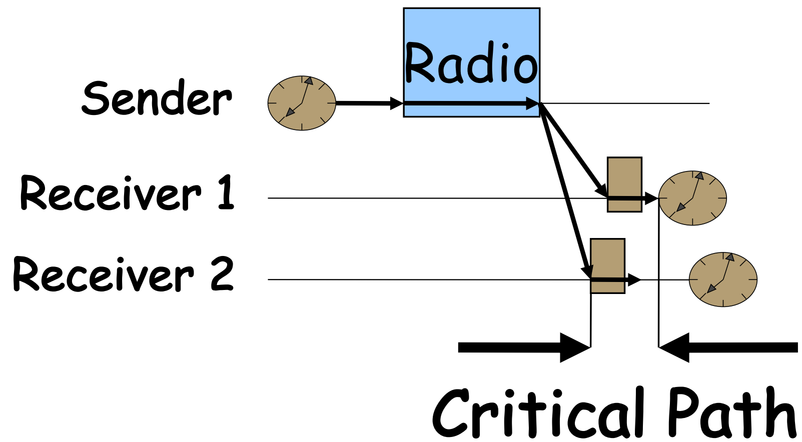
TRADITIONAL SYNCH vs RBS



Traditional Critical Path:

From the time the sender reads its clock, to when the receiver reads the packet *and* its clock

Nondeterministic delay: Send time and Access time. Receiver time small.



RBS: Only sensitive to the differences in receive time and propagation delay

Critical path length is shortened to include only the time from the injection of the packet into the channel to the last clock read.

(Send time and Access time are eliminated!)

Reference-Broadcast Synchronization (RBS)

- Algorithm to Estimate the Phase Offset between the Clocks of Two Receivers
- A transmitter broadcasts a reference packet to two (or more) receivers
- Each receiver records the time at which the packet was received according to its local clock

Reference-Broadcast Synchronization (RBS)

- The receivers exchange the observed times at which they received the packet.
- The clock offset between two receivers is computed as the difference of the local times at which the receivers received the same message.

Observations about RBS

- RBS removes SEND and ACCESS TIME errors
- Broadcast packet is used as a relative time reference

Observations about RBS

- Each receiver synchronizes to a reference packet
  - Ref. packet is injected into the channel at the same instant for all receivers
- Broadcast packet does not contain timestamp
  - Almost any broadcast packet can be used, e.g ARP, RTS/CTS, route discovery packets, etc

Phase Offset Estimation

- RBS can produce highly accurate results if
  - Message reception by each receiver is high
  - Each receiver can record its local clock reading as soon as the message is received.

Phase Offset Estimation

- Receiver i will compute its offset relative to any other receiver j as the average of clock differences for each packet received by nodes i and j:
- Result: For all i,j, ε, n:

$$Offset[i,j] = \frac{1}{m}\sum_{k=1}^{m}\left(T_{j,k} - T_{i,k}\right)$$

n: Number of receivers
m: Number of reference broadcasts
$T_{i,k}$: Node i's clock when it receives the broadcast k

Advantages of the RBS Scheme

- Largest sources of error (send and access times) are removed from the critical path by decoupling the sender from the receivers.
- Clock offset and skew are estimated independently of each other
- In addition, clock correction does not interfere with either estimation because local clocks are never modified
- Post-facto synchronization prevents energy from being wasted on expensive clock updates

Disadvantages of the RBS Scheme

- For a single-hop network of n nodes, it requires $O(n^2)$ message exchanges (computationally expensive for dense networks)
- Convergence time can be high due to large number of message exchanges.

Disadvantages of the RBS Scheme

- Reference sender is left unsynchronized in this method.
- If reference sender needs to be synchronized, it will lead to a significant waste of energy

Disadvantages of the RBS Scheme

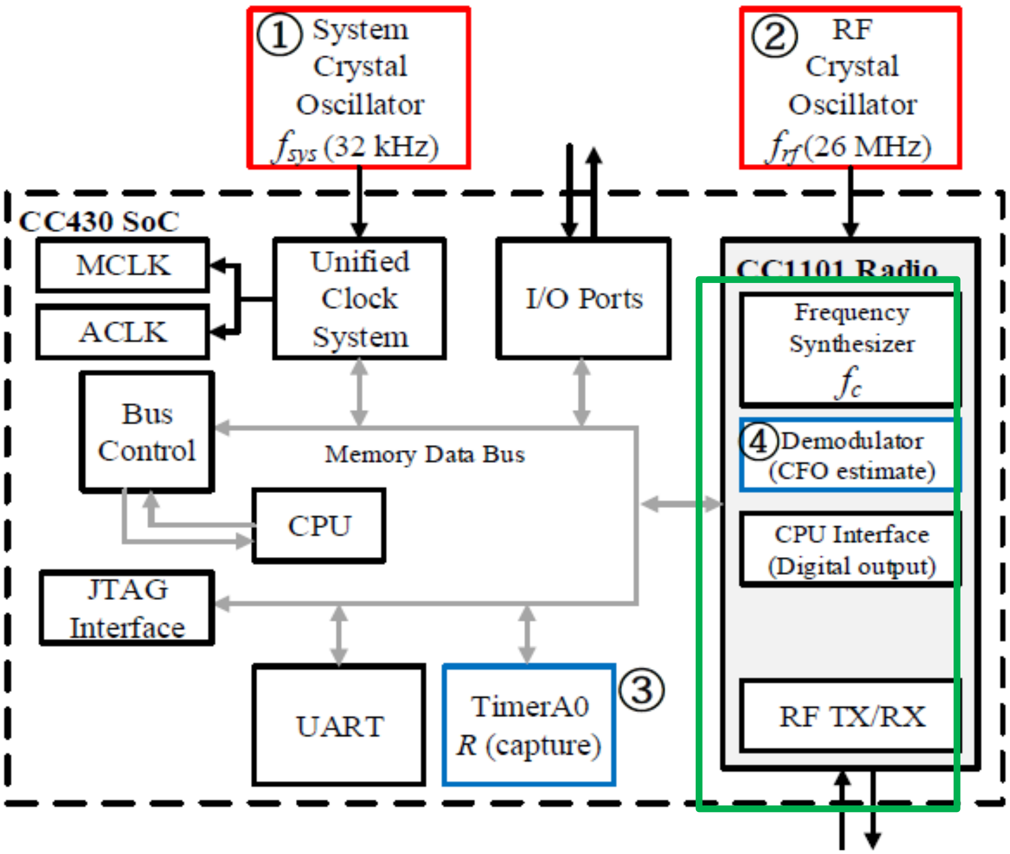
- Limited to only one broadcast domain
- Translation errors and forwarding delays: make RBS impractical and time difference may occur
- Different time-of-occurrences may occur at different sinks

Can we do better?

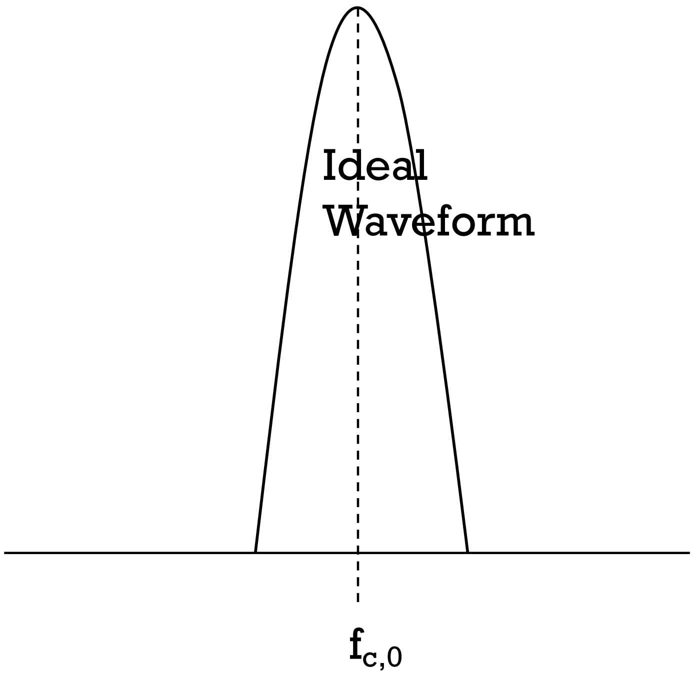
Clock Syntonization

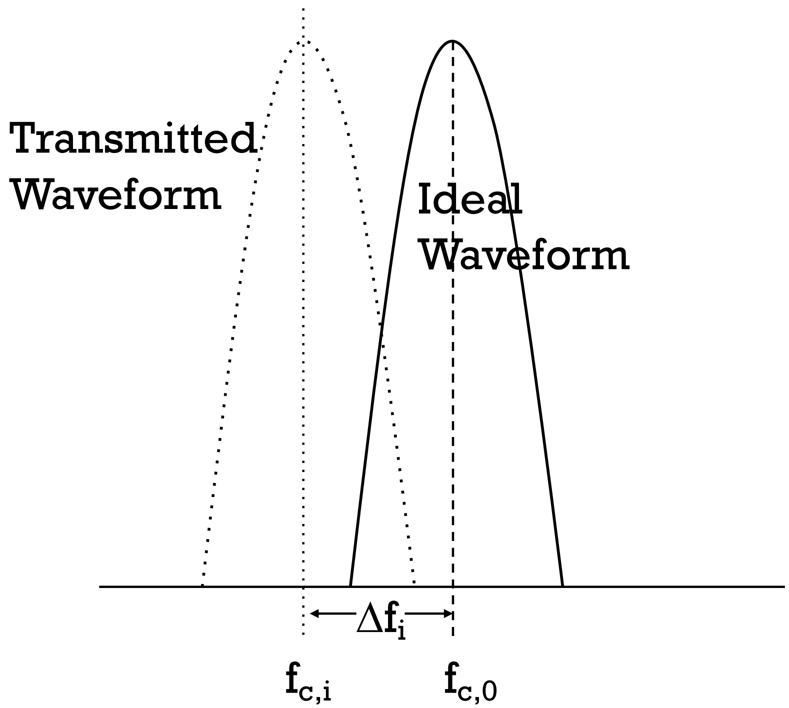
- Clock Offset: Difference in time between two clock values
- Time Synchronization: Minimization of relative offset
- Clock Skew: Difference in frequency between two clock frequencies
- Syntonization: Minimization of relative skew
- Clock syntonization = Frequency synchronization

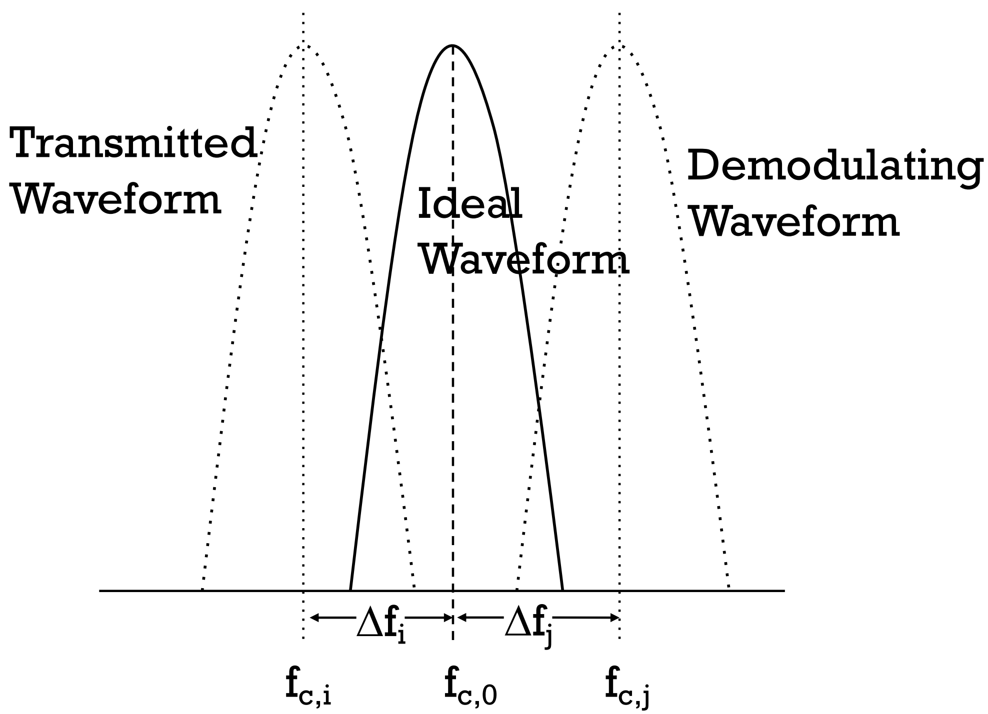
- IoT hardware system structure

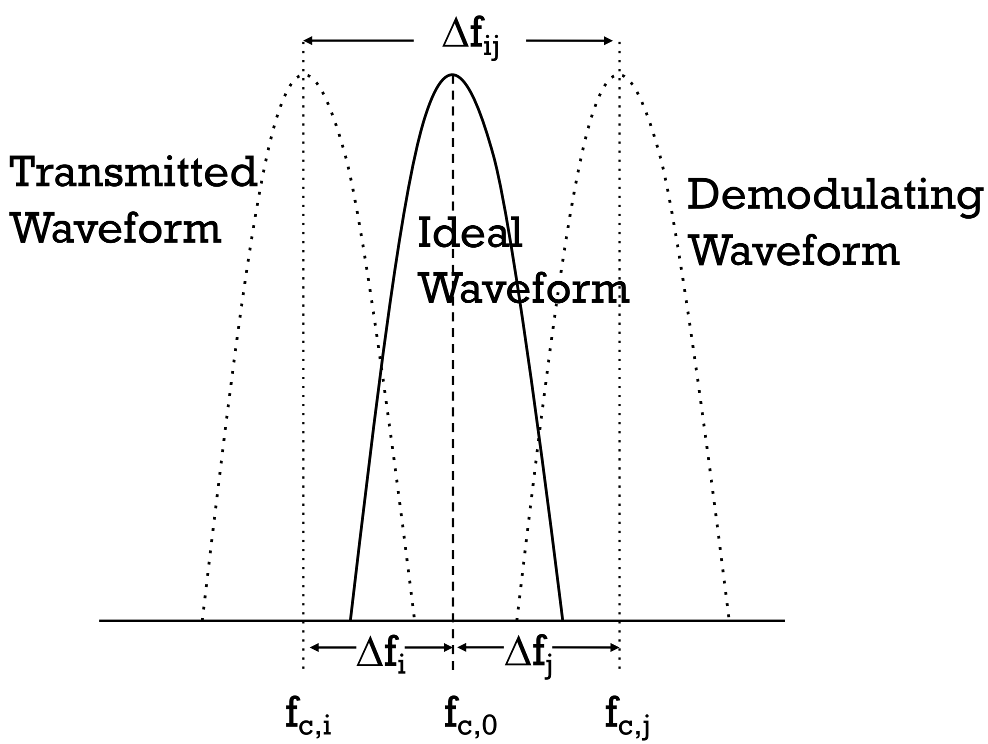


"MSP430 SoC With RF core," Texas Instruments, Tech. Pep.SLAS554,Sep,2013

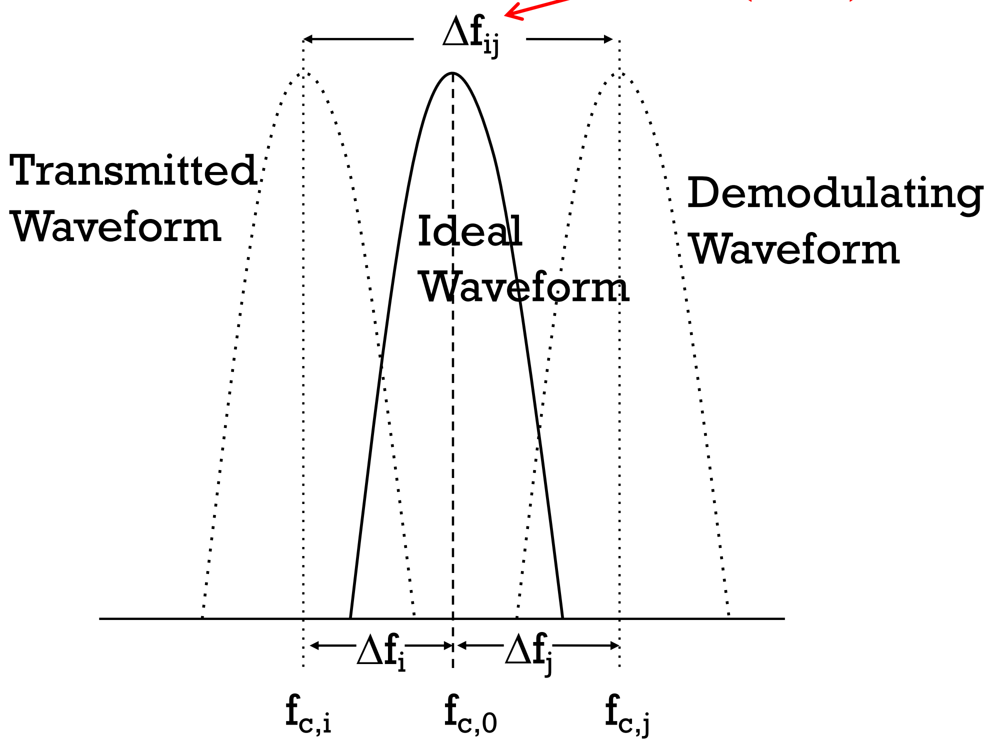

Ideal
Waveform
$f_{c,0}$

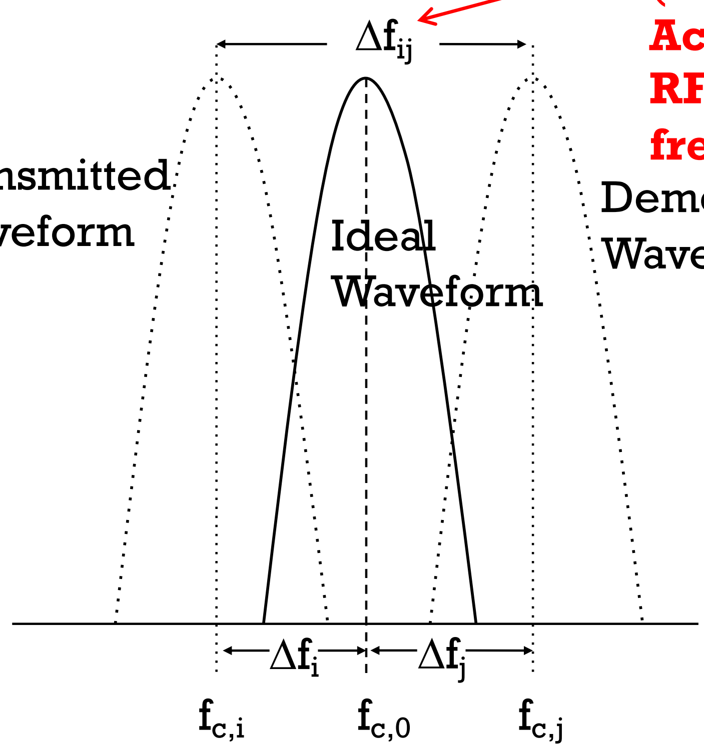

Transmitted
Waveform
Ideal
Waveform
Δf_i
$f_{c,i}$
$f_{c,0}$


Transmitted
Waveform
Ideal
Waveform
Demodulating
Waveform
Δf_i
Δf_j
$f_{c,i}$
$f_{c,0}$
$f_{c,j}$


Δf_ij
Transmitted Waveform
Ideal Waveform
Demodulating Waveform
Δf_i
Δf_j
f_c,i
f_c,0
f_c,j

Carrier frequency offset (CFO)

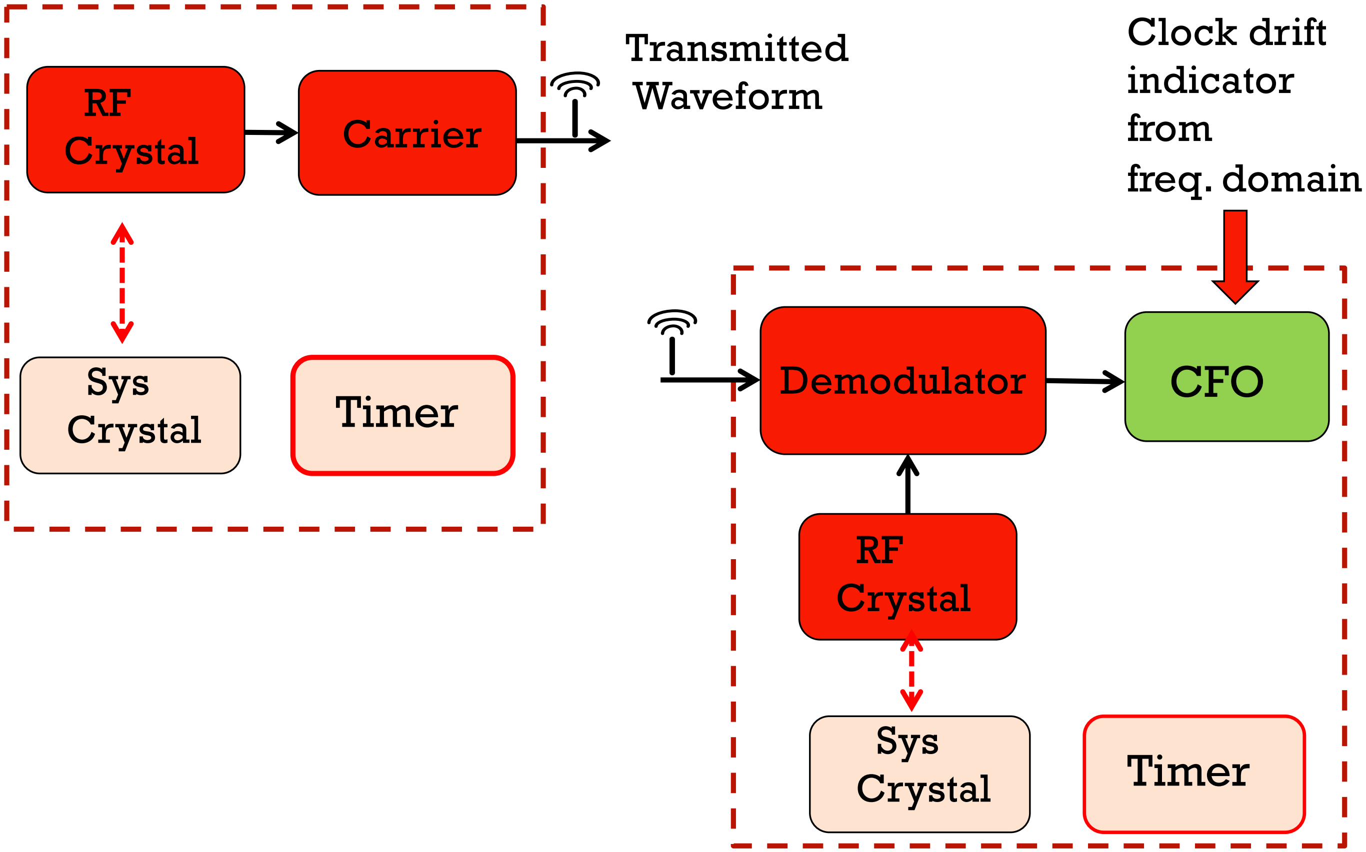


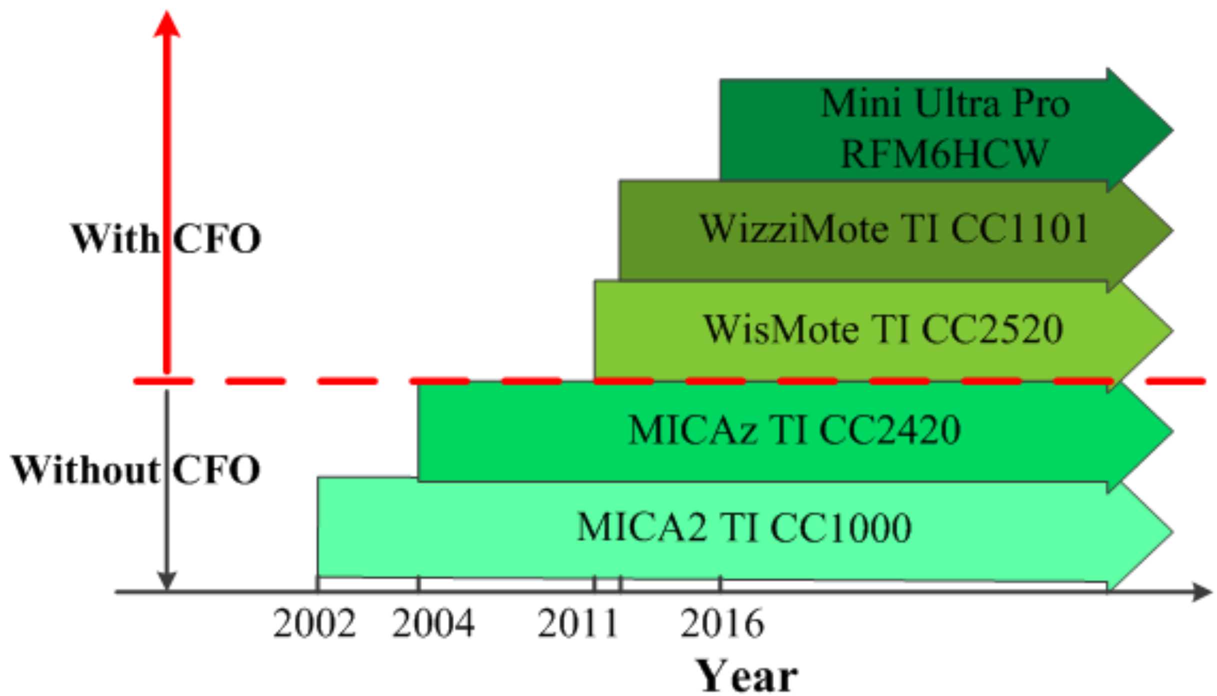


Carrier frequency offset (CFO)

Accurate indicator of RF clock drift in frequency domain

Principle Diagram




Mini Ultra Pro
RFM6HCW
WizziMote TI CC1101
WisMote TI CC2520
MICAz TI CC2420
MICA2 TI CC1000
With CFO
Without CFO
2002
2004
2011
2016
Year

Clock Syntonization using CFO Information

Contributions

B. Zhou, F. Guo, and M. C. Vuran, "Timestamp-Free Clock Syntonization for IoT Using Carrier Frequency Offset", IEEE Transactions on Mobile Computing, vol. 21, no. 2, pp. 712-727, Feb 2022 (IEEE INFOCOM 2017).

- New way to estimate clock skew by leveraging CFO
- Model of CFO capturing clock skew
- Single message transmitted for time syntonization
- Novel experiment methodology

Did he touch the ball?

FIFA World Cup 22 Soccer Ball

FIFA World Cup 22 Soccer Ball

Source: https://www.footyheadlines.com/2022/07/world-cup-match-ball-to-contain-sensor.html

FIFA World Cup 22 Soccer Ball

- Adidas Al Rihla match ball
- Adidas Suspension System
- 500Hz inertial measurement unit (IMU) motion sensor
- Real-time transmission to VAR team
- Connected Ball technology
- Offside detection
- Goal-line technology
- and…

Source: https://www.footyheadlines.com/2022/07/world-cup-match-ball-to-contain-sensor.html

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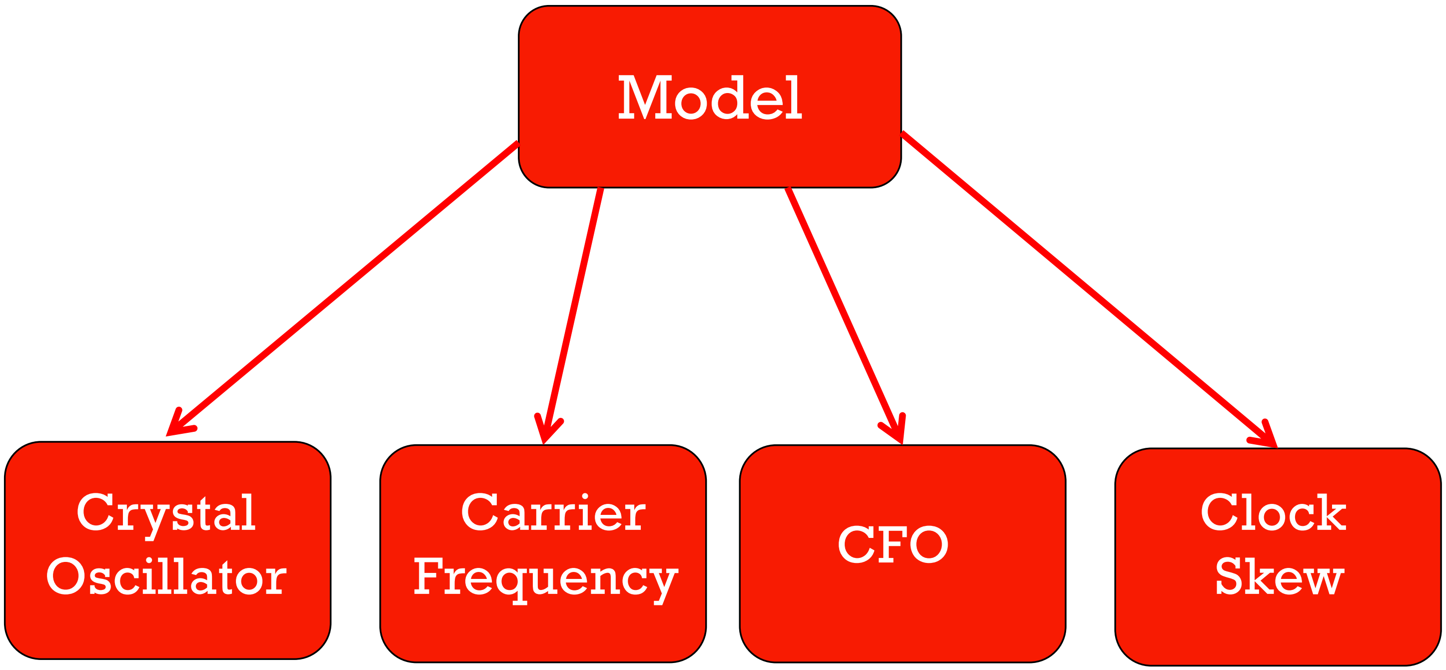

Model
Crystal Oscillator
Carrier Frequency
CFO
Clock Skew

Crystal Oscillator Model

- Assuming time invariant

$$f_{x,i} = f_{x,0} + \delta_x$$

$$\delta_x \sim \mathcal{N}(0, 10^6 \rho)$$

- $f_{x,0}$: nominal frequency of clock x
- δ_x: inaccuracy of the oscillator frequency
- ρ: the parts-per-million rate (ppm)

I. R. C. Committee et al., "Characterization of frequency and phase noise," 1986
Quitin and et.al., "A scalable architecture for distributed transmit beamforming with commodity radios: Design and proof of concept," IEEE Transactions on Wireless Communications, vol. 12, no. 3, pp. 1418–1428, 2013.

Carrier Frequency Model

- Ideal carrier frequency

$$f_{c,0} = \underbrace{N}_{\text{Frequency divider gain}} \cdot \underbrace{f_{rf,0}}_{\text{Nominal reference frequency}}$$

- Carrier frequency with error from PLL

$$f_{c,i} = N \cdot f_{rf,i} + \underbrace{\delta_{PLL,i}}_{\text{Error from PLL}} = N \cdot (f_{rf,0} + \underbrace{\delta_{rf,0}}_{\text{Reference crystal error}}) + \delta_{PLL,i}$$

$$\sigma_{\delta_{PLL}} = \sqrt{2 \cdot \int_{f_a}^{f_b} \underbrace{L(f)}_{\text{Power spectrum density of phase noise}} \cdot f^2 df}$$

S. Mendel and C. Vogel, "A z-domain model and analysis of phasedomain all-digital phase-locked loops," in Norchip, 2007. IEEE, 2007,pp. 1–6.
D. Banerjee, PLL performance, simulation and design. Dog Ear Publishing, 2006.

CFO Model

How is the CFO obtained?

- Receiver end demodulation
  - CFO theoretical model:

$$\Delta f_c = \underline{f_{c,j}} - \underline{f_{c,i}}$$

Receiver's carrier freq.

Transmitter's carrier freq.

By plugging carrier model

$$\begin{aligned}\Delta f_c &= \{N f_{rf,j} + \delta_{PLL,j}\} - \{N f_{rf,i} + \delta_{PLL,i}\} \\ &= N \cdot \Delta f_{rf} + \Delta\delta_{PLL} \ ,\end{aligned}$$

Clock Skew Model

- IRCF measurement (Internal Relative Clock Frequency)

$$R_i = \frac{f_{rf,i}}{f_{sys,i}} \Rightarrow \left.\begin{aligned} f_{rf,i} &= R_i \cdot f_{sys,i} \\ f_{rf,j} &= R_j \cdot f_{sys,j} \end{aligned}\right\} \widehat{\Delta f}^{\dagger}_{rf} = R_j \cdot f_{sys,j} - R_i \cdot f_{sys,i}$$

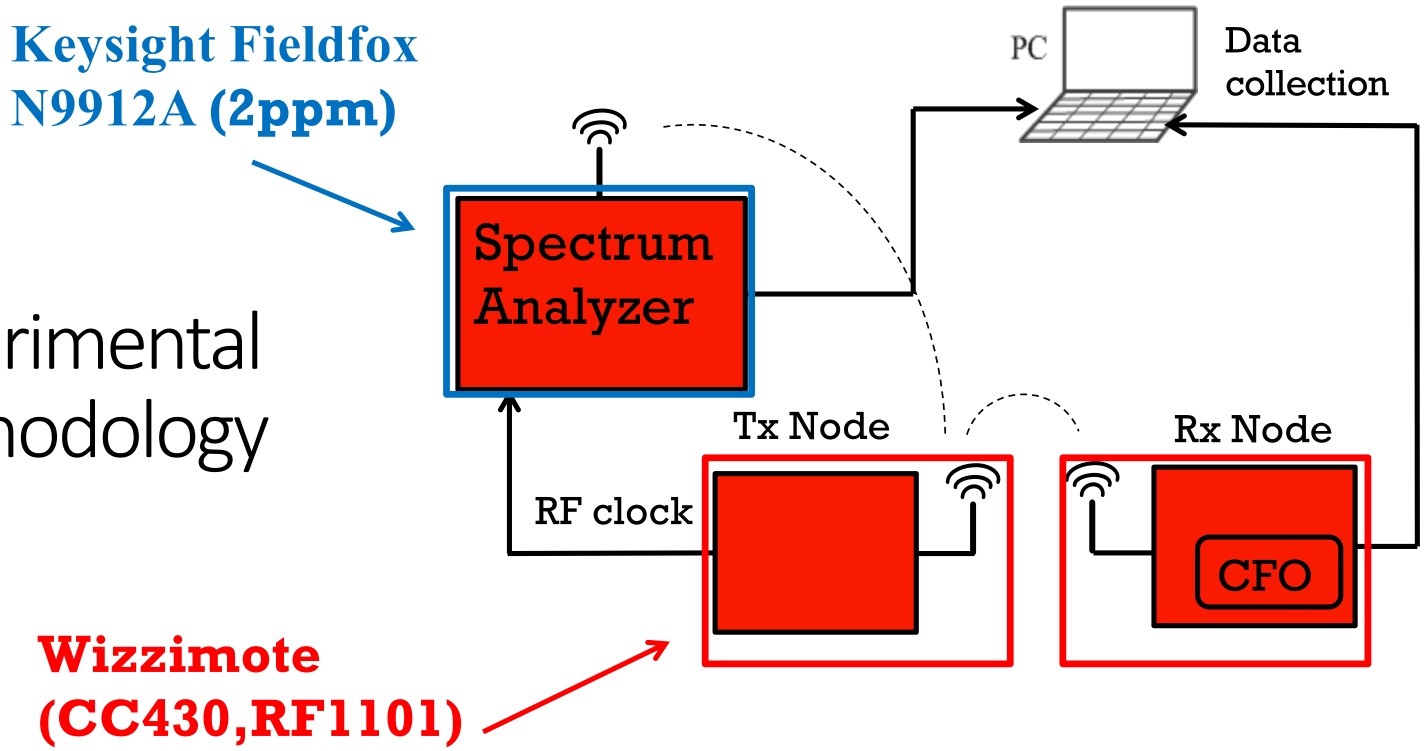
$$\begin{cases} \dfrac{\widehat{\Delta f}_c - \Delta\delta_{PLL}}{N} = R_j \cdot f_{sys,j} - R_i \cdot f_{sys,i} \\ \widehat{\Delta f}_{sys} = f_{sys,j} - f_{sys,i} \end{cases}$$

$$\widehat{\Delta f}_{sys} = \frac{\frac{1}{N}\{\widehat{\Delta f}_c - \Delta\delta_{PLL}\} + (R_i - R_j) \cdot f_{sys,i}}{R_j}$$

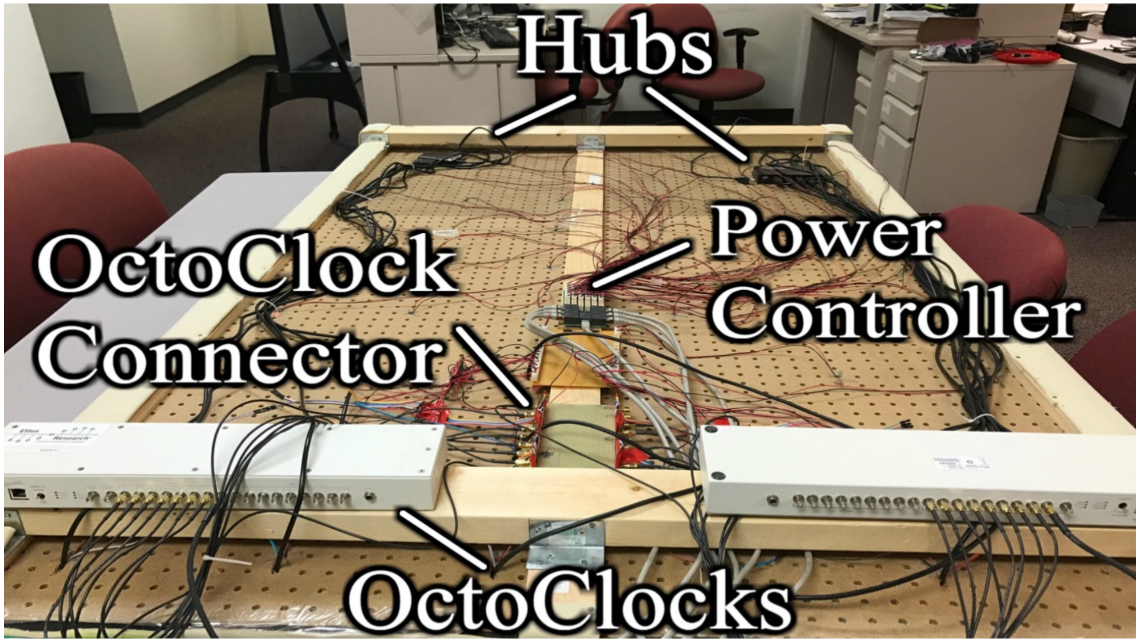
Experimental Methodology

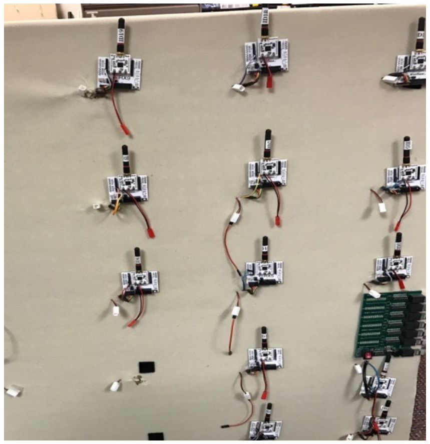
- Ground truth information collection
- Pairwise clock skew estimation

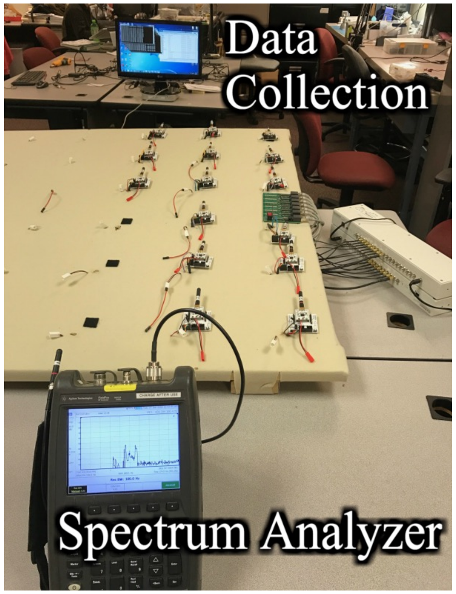
Experimental Methodology



Testbed







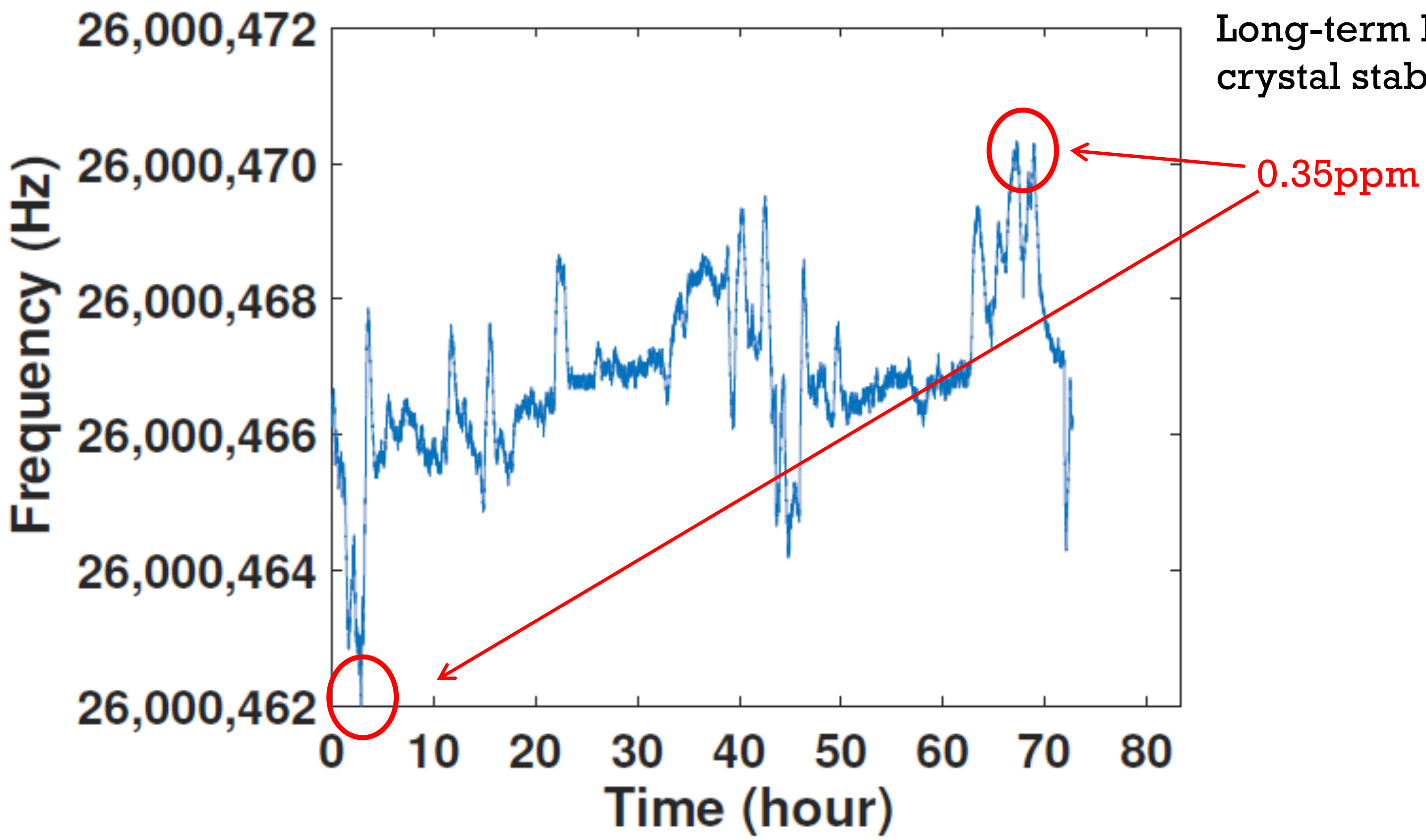
B. Zhou,F. Guo, and M. C. Vuran, "Demo Abstract: Clock Syntonization using CFO Information in Wireless Sensor Networks ", in Proc. of IEEE INFOCOM 2017, Atlanta, GA, May 2017

Model Validation

- Accuracy and stability of RF clock
- Accuracy of CFO register value
- CFO from register vs RFCLK offset

Model Validation

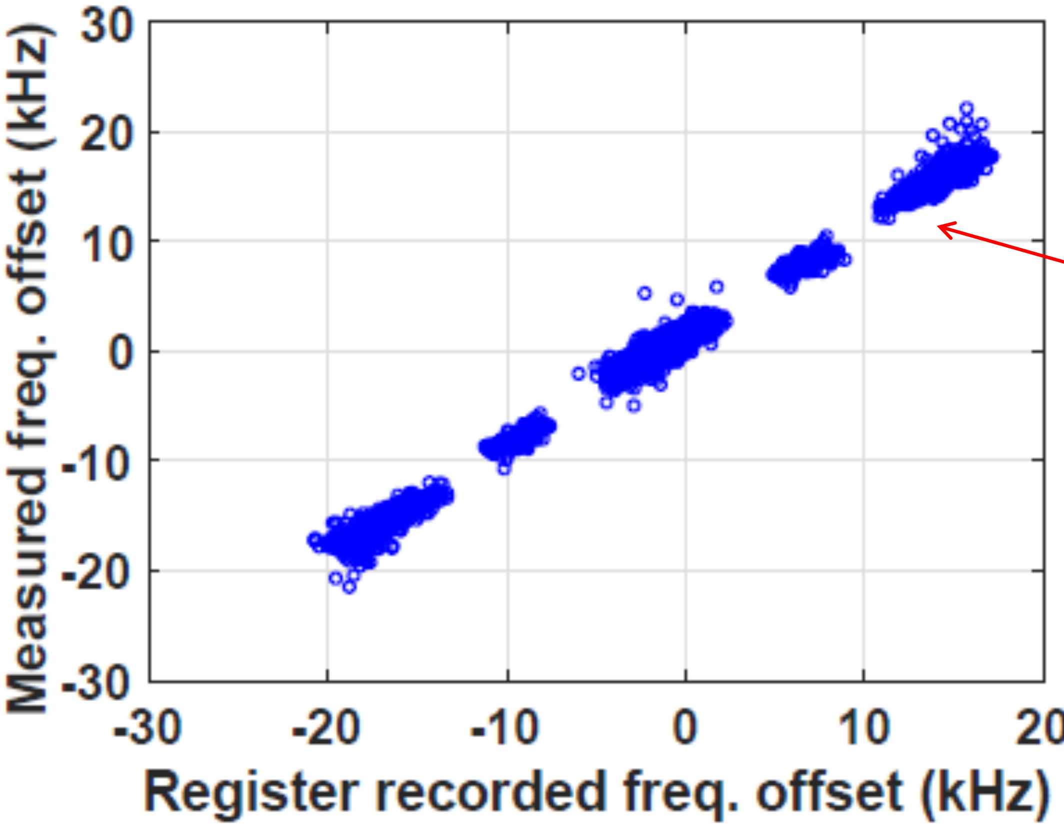
- Reference frequency validation



Long-term RF crystal stability:

Model Validation

- CFO Register accuracy validation



- Ideal Model:

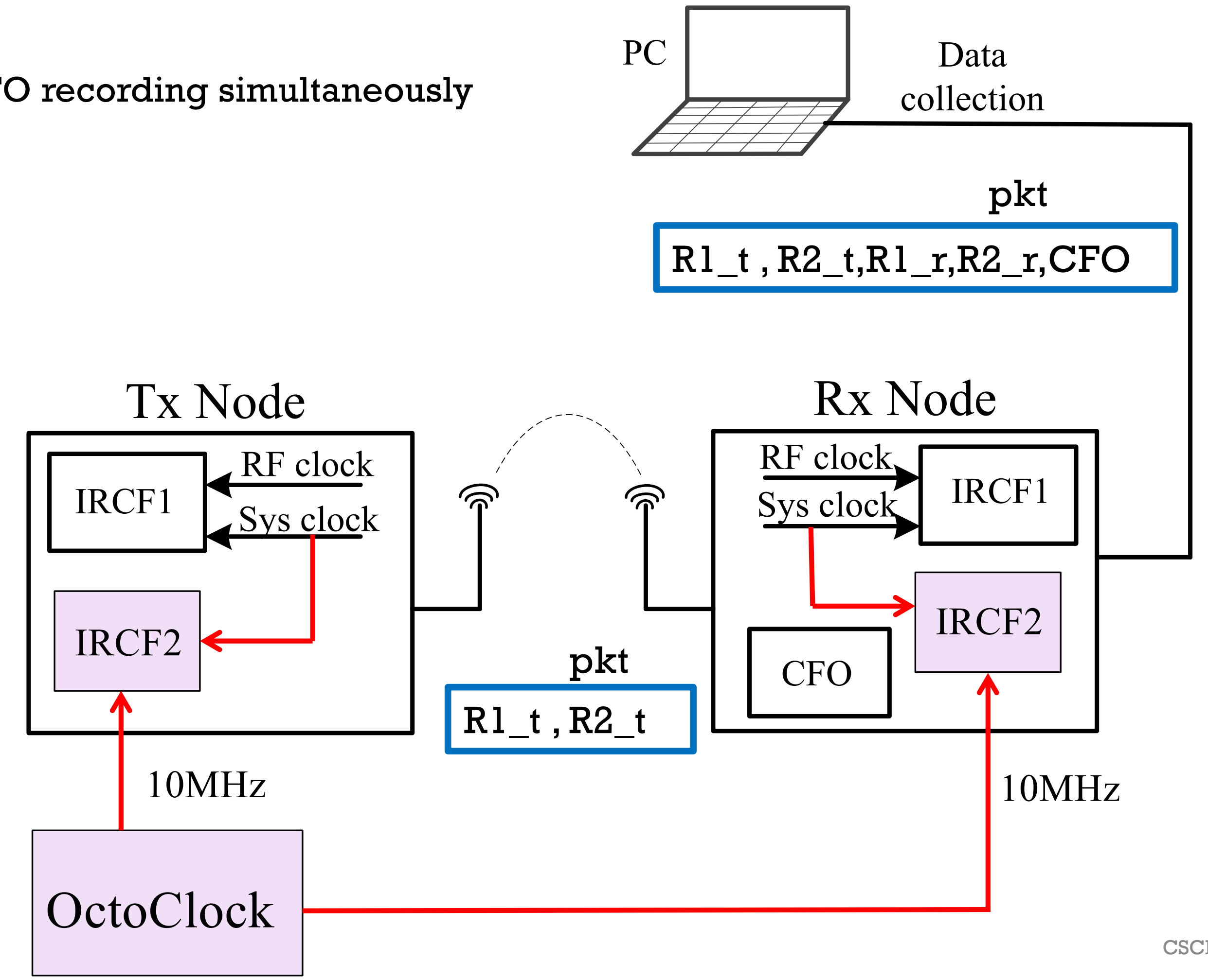
$$\widehat{\Delta f}_c = \theta_{CFO} + \delta_{CFO}$$

- Linear regression (95% confidence):

Parameters	**Value**
Slope	1.005
Intercept	1.24
R^2	**0.9952**
RMSE	0.7353

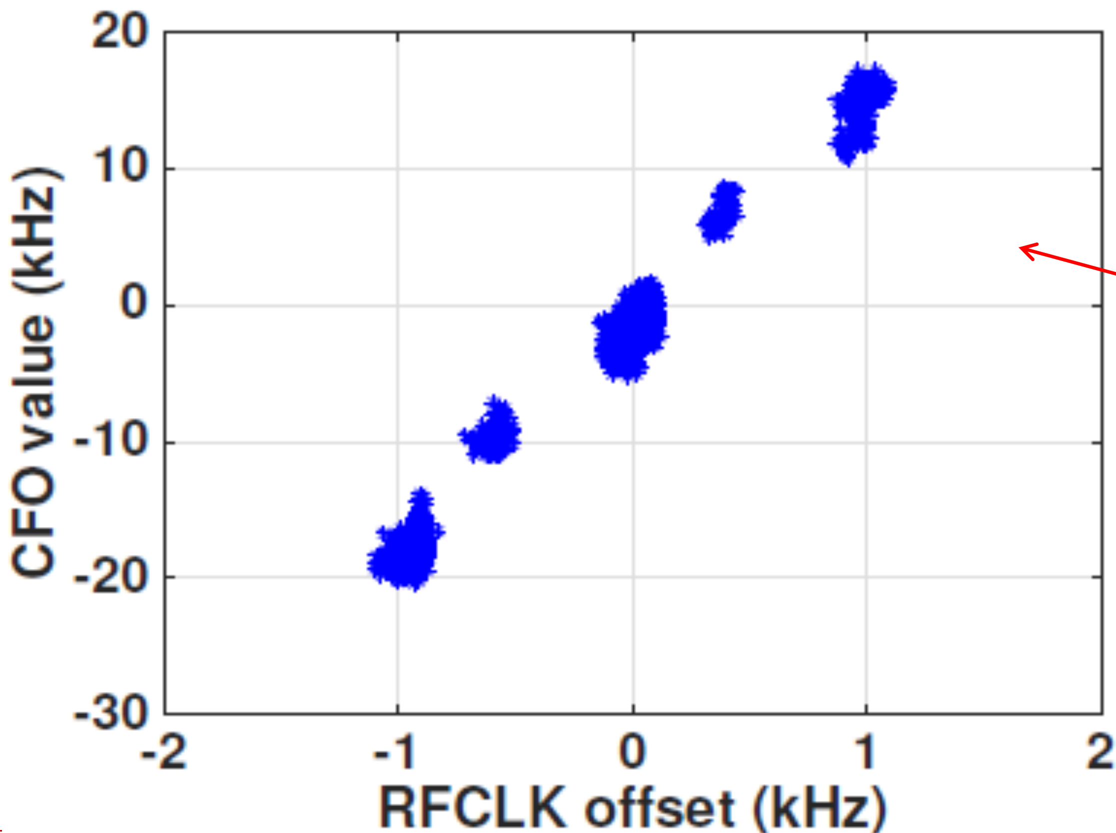
Pairwise Clock Skew Estimation

- 15 nodes
- IRCF and CFO recording simultaneously



Model Validation

CFO value with RFCLK model validation



- Ideal Model:

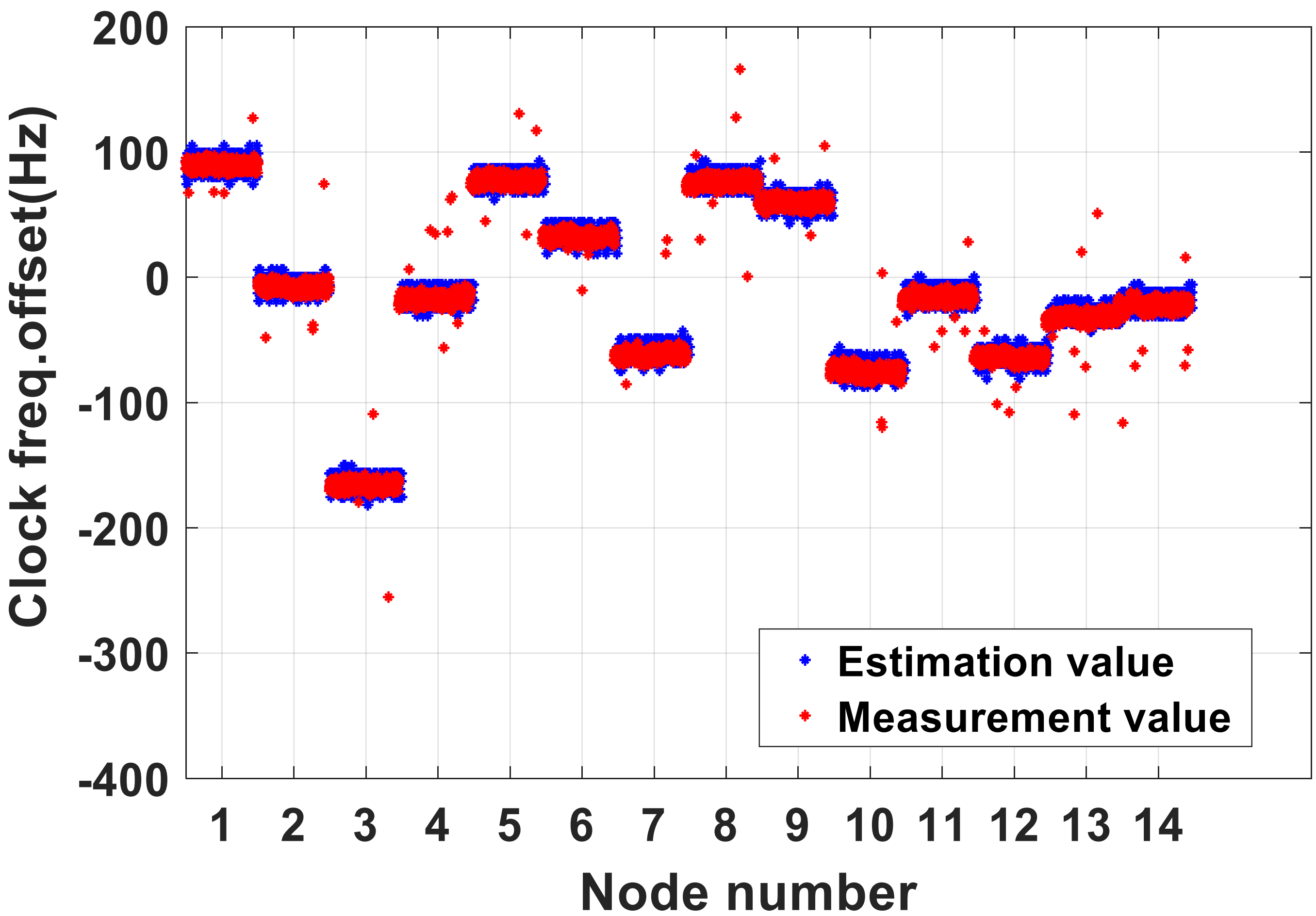
$$\Delta f_c := \underline{N} \cdot \Delta f_{rf} + \Delta\delta_{PLL}$$

16.69

- Linear regression (95% confidence):

Parameters	Value
Slope	17.11
Intercept	-1.606
R^2	**0.9857**
RMSE	1.281

Pairwise Clock Skew Estimation



Mean error: 2.4637 Hz

Standard deviation: 6.9376 Hz

Synchronization Protocol	Messaging Scheme
NTP: Network Time Protocol	Two-way
PTP: Precision Time Protocol	Two-way
TPSN: Time-synchronization Protocol for Sensor Networks	Two-way
RBS: Reference Broadcast Protocol	Receiver-receiver
FTSP: Flooding Time Synchronization Protocol	One-way
FCSA: Flooding with Clock Speed Agreement	One-way
R-Sync: Robust Synchronization	Receiver-only
TDP: Time Diffusion Protocol	Two-way
DTSP: Distributed Time Synchronization Protocol	One-way
GTSP: Gradient Synchronization Protocol	One-way
ATS: Average Time Synchronization	One-way
RFA: Reachback Firefly	One-way
CFO-Synt: CFO-based Syntonization	One-way

Which concept was the most intriguing? (one word)

Total Results: 0

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Exam 2

- Friday, Dec. 2nd, in class at 9:30am
- Coverage: Communication, MAC, Error Control, Localization, Synchronization
- Open book/notes, everything allowed except for digital media (laptop, phone, tablet, etc)
- Sample questions will be posted on Canvas