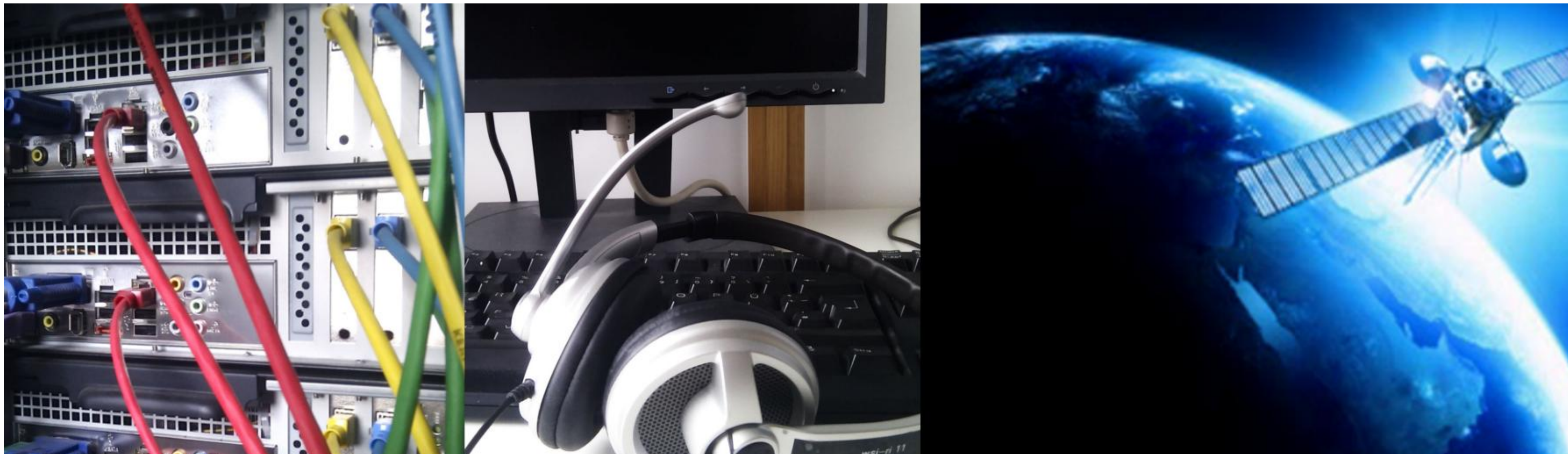
EBERHARD KARLS UNIVERSITÄT TÜBINGEN

MATHEMATISCH-NATURWISSENSCHAFTLICHE FAKULTÄT

ICS – Interactive Communication Systems



Precise Time of Flight Measurements in IEEE 802.11 Networks by Cross-Correlating the Sampled Signal with a Continuous Barker Code

08.11.2010

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Wir stiften Zukunft

Agenda

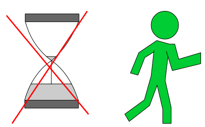
- Motivation & Introduction
- Technical Introduction
- Improving Timestamps
- Performance Evaluation
- Summary & Conclusions

What is it about? Why do we need it?

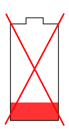
MOTIVATION & INTRODUCTION

What is the aim?

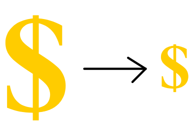
- A GPS-like indoor localization…
- But, indoors we need a higher accuracy.



- We cannot “wait a minute“ for localization.
- Localization working “continuously“ while we walk

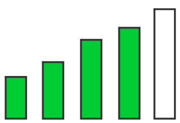


- Reduce energy consumption



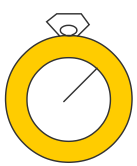
- Indoor navigation shall be cheap.
- Thus, we try to use already available infrastructure and only few additional devices.

Localization Methods (Using IEEE 802.11)



Signal strength (RSSI)

- Higher distance => lower received signal strength
- Fingerprinting maps (high effort!) needed because of multipath & fading

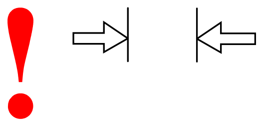


Time of flight (TOF)

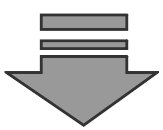
- Higher distance => longer transport time
- Knowing arrival times and speed (= speed of light), we can calculate the distance.
- But: Timestamps must be very accurate! (1 µs ~ 300 m)

Existing IEEE 802.11 Infrastructure

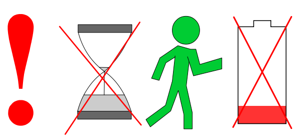
- Is very cheap (for free?)



- Off-the-shelf hardware has only 1 µs (=300 m) timestamp resolution!



Solution, with drawbacks



- Many measurements averaged (ca. 500 for ~ 3 m accuracy on avg.)
- Increased delay and energy consumption

Using Software Defined Radios (SDRs)

- Improves timestamp resolution
- Fewer measurements needed

! $ → $

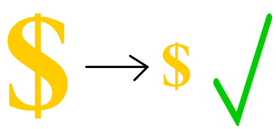
- But :SDRs are expensive!
- We cannot replace the whole “infrastructure“…

√ $ → $

Our solution uses

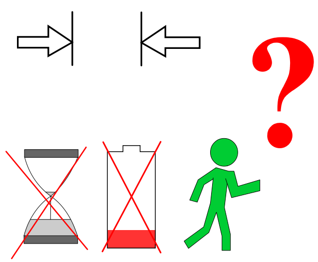
- Available infrastructure
- One *monitor device*
  - implemented as SDR software
  - measures *distances between other nodes*

What is the paper about?



Our previous work

- A (passive) monitor device can measure distances between other nodes by observing their communication.
- We used off-the-shelf hardware as monitor devices.



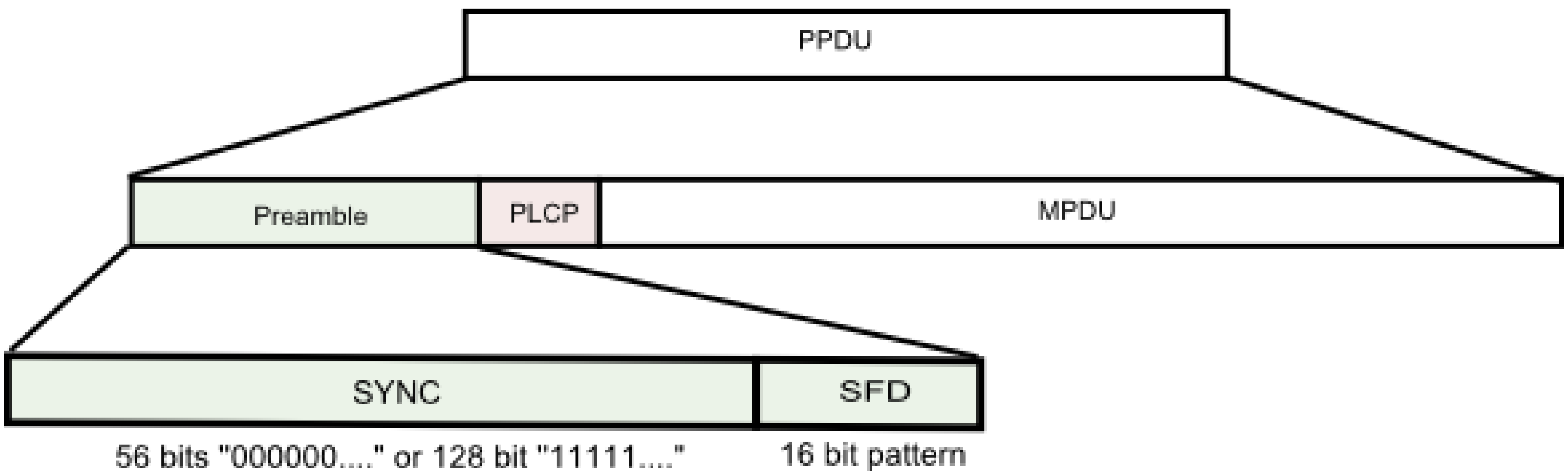
Focus of current paper

- Improve timestamp resolution (using SDRs)
- Increase overall accuracy
- Reduce number of measurement samples

IEEE 802.11 Signal Modulation and TOF Measurements

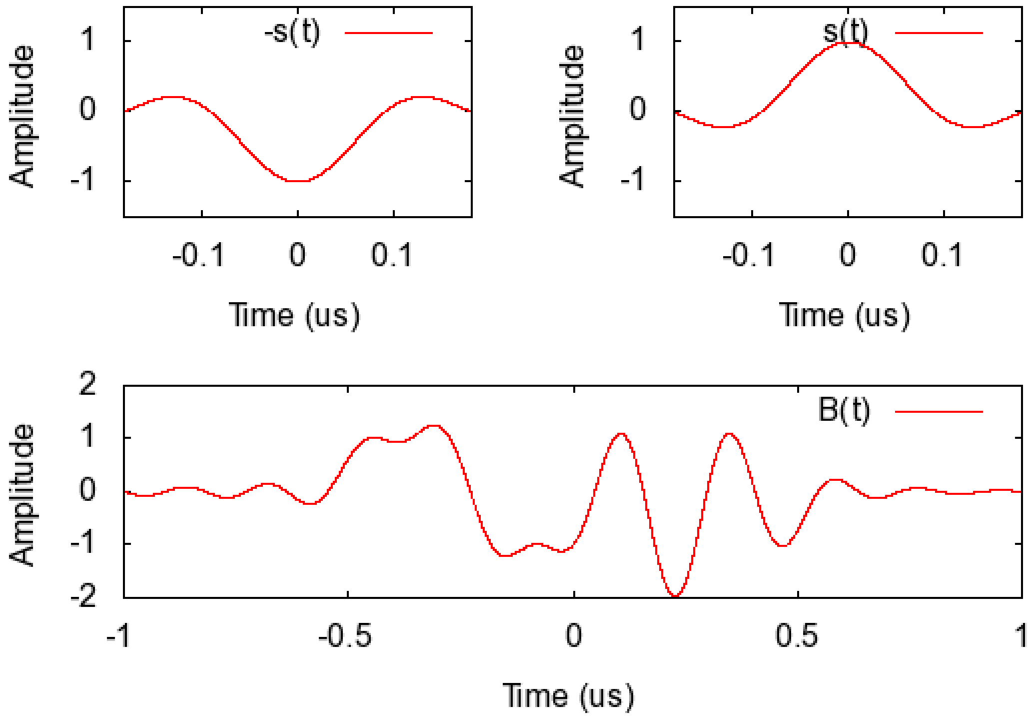
TECHNICAL INTRODUCTION

General 802.11 Frame Structure (DSSS-PHY)



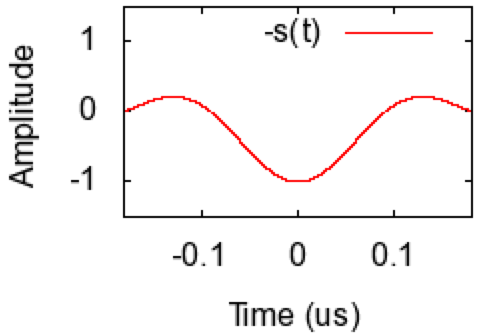
- SYNC used for synchronization to signal
- SFD (Start Frame Delimiter) marks beginning of data
- Timestamp is taken at SFD

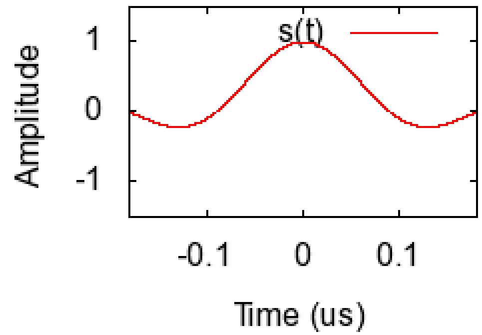
Synchronization – Barker Code Modulation



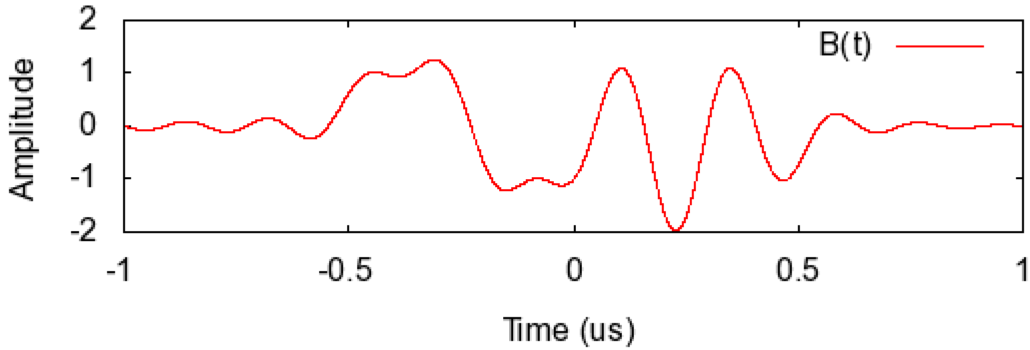
- Coding of preamble and SFD

Synchronization – Barker Code Modulation





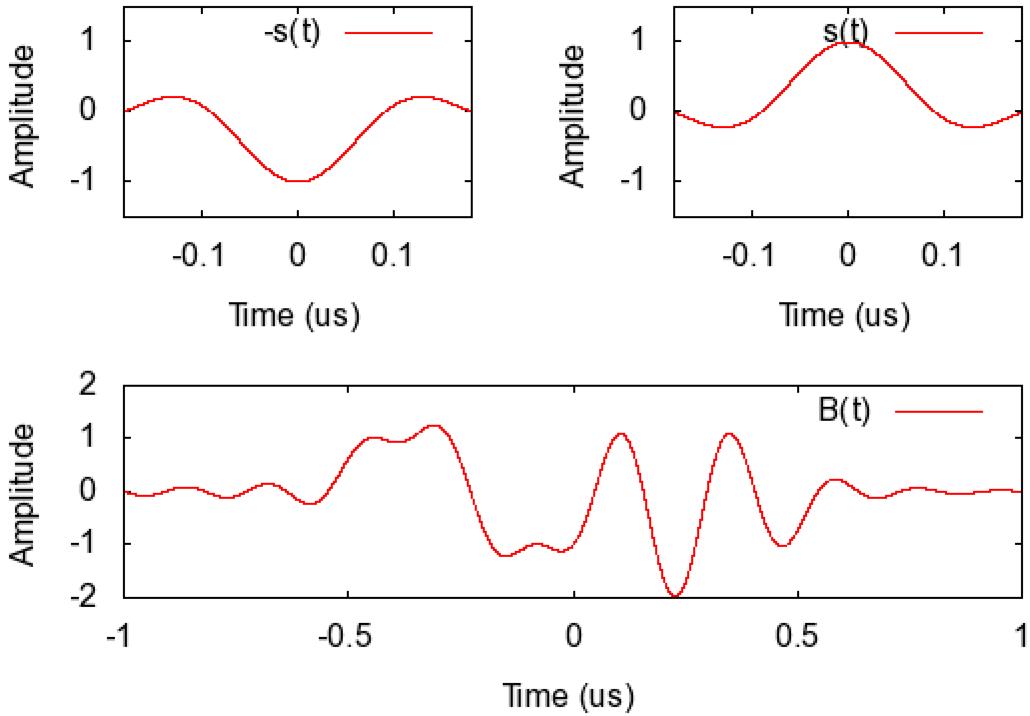
$$
\begin{aligned}
sinc(t) &:= \begin{cases} \sin(t)/t, & t \neq 0 \\ 1, & t = 0 \end{cases} \\
s(t) &:= sinc(2\pi t/T_c) \\
s_0(t) &:= s(t) \\
s_1(t) &:= -s(t)
\end{aligned}
$$



$$
\begin{aligned}
b_k &:= \{+1, +1, +1, -1, -1, -1, \\
&\qquad +1, -1, -1, +1, -1 \} \\
B(t) &:= \sum_{k=1}^{11} b_k * s(t + T_c * (k-6))
\end{aligned}
$$

- Coding of preamble and SFD

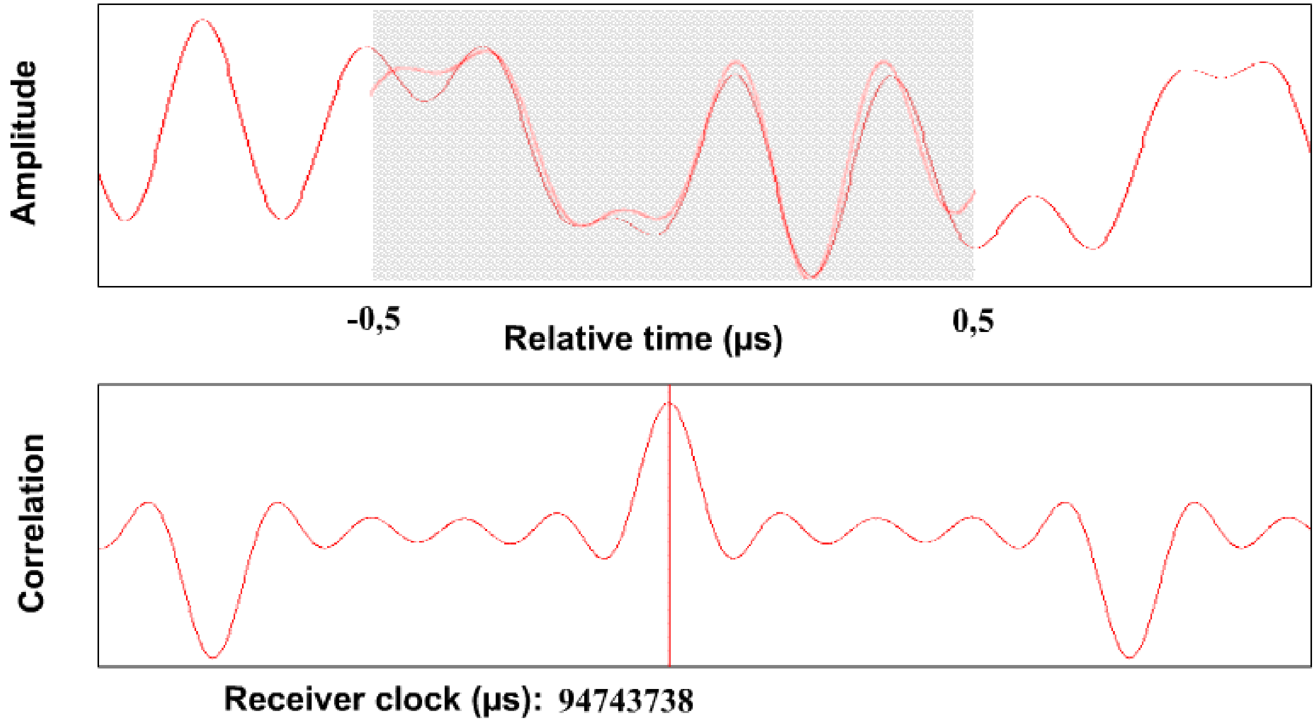
Synchronization – Barker Code Modulation



Time continuous form can be calculated!

- Coding of preamble and SFD
- Based on 11-chip Barker code b_k := { 1, 1, 1, 0, 0, 0, 1, 0, 0, 1, 0 }
- Good autocorrelation properties, enabling synchronization

1 µs Precision Method (Off-the-Shelf Hardware)

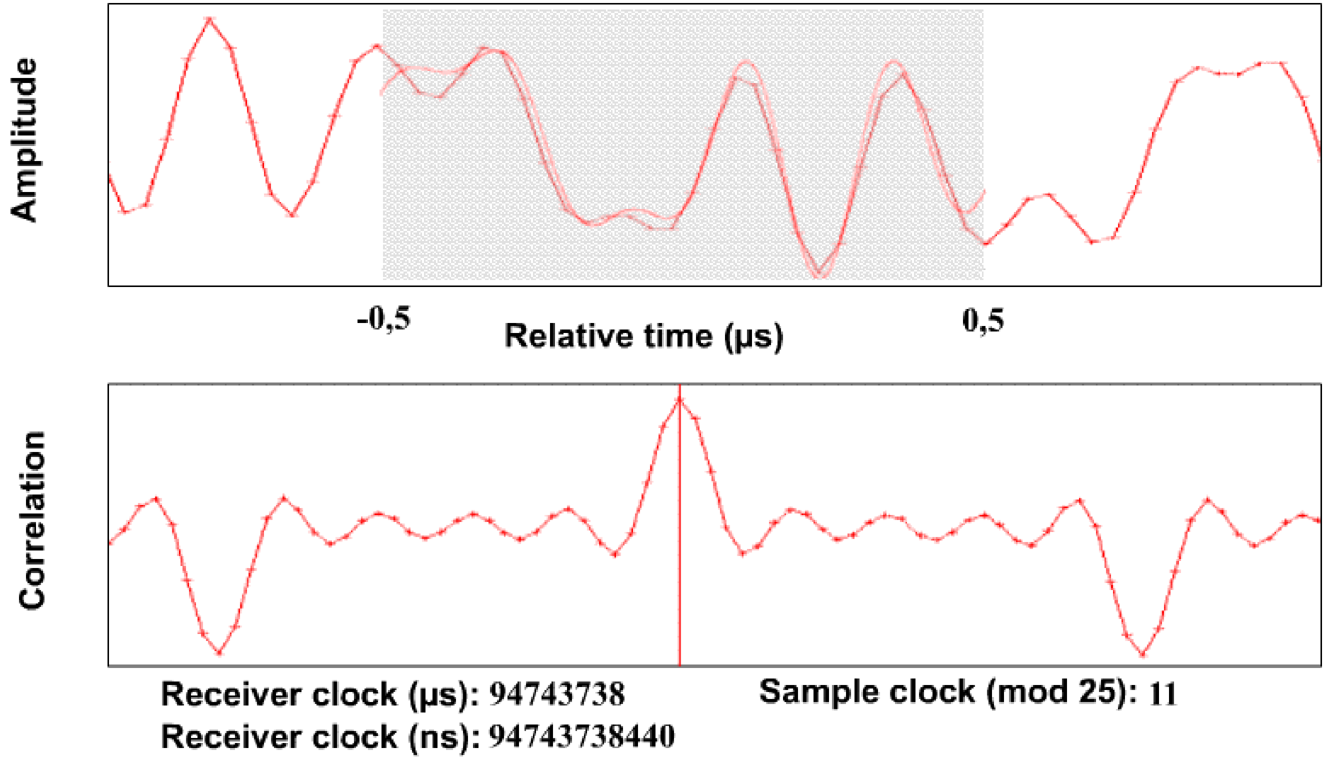


- Accuracy of timestamps is 1 µs
- Clock independent from signal synchronization

How did you improve the accuracy?

OUR IMPROVEMENTS…

Sample Precision Method



- Relative time offset of the synchronization can be used to improve timestamps (+/- 20 ns at 25 Msps)

How To Achieve Subsample Precision?

First Guess: Interpolate received samples => higher resolution

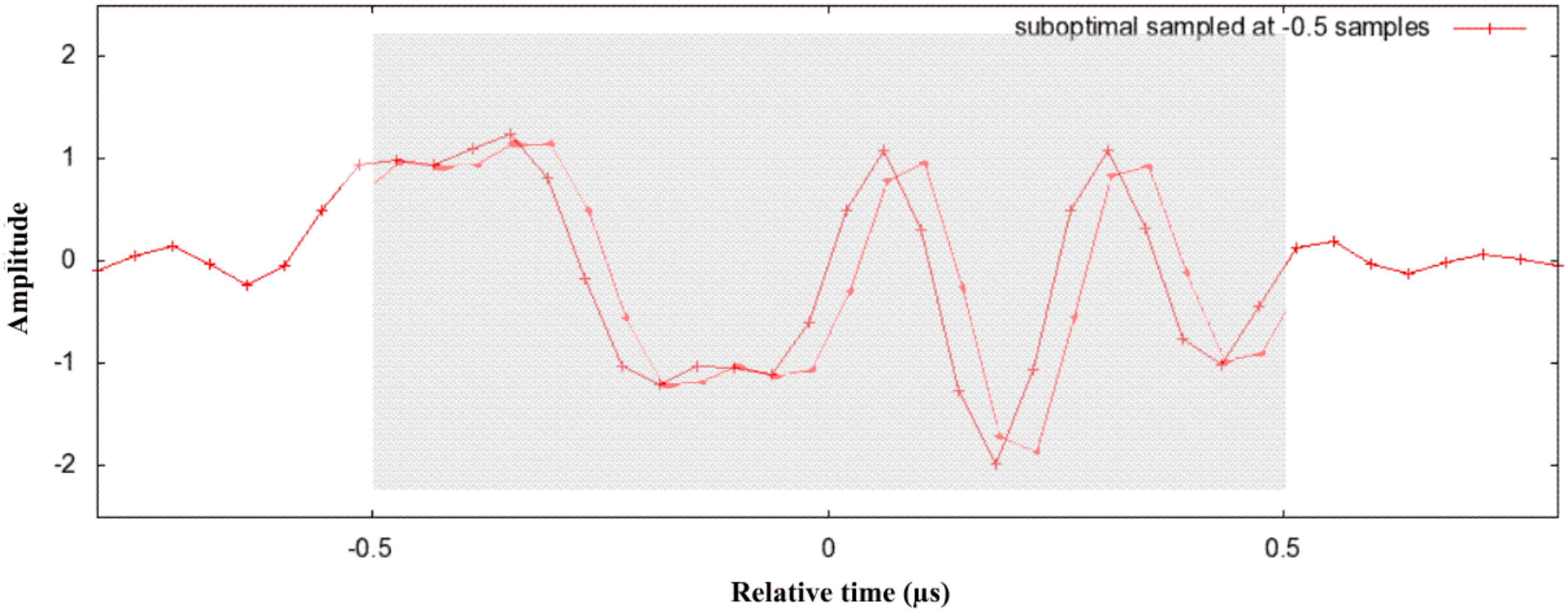
Problems

- Interpolation costs additional resources.
- Which interpolation algorithm is the right one?
- It "interpolates" the noise in the received signal, too.

Our approach

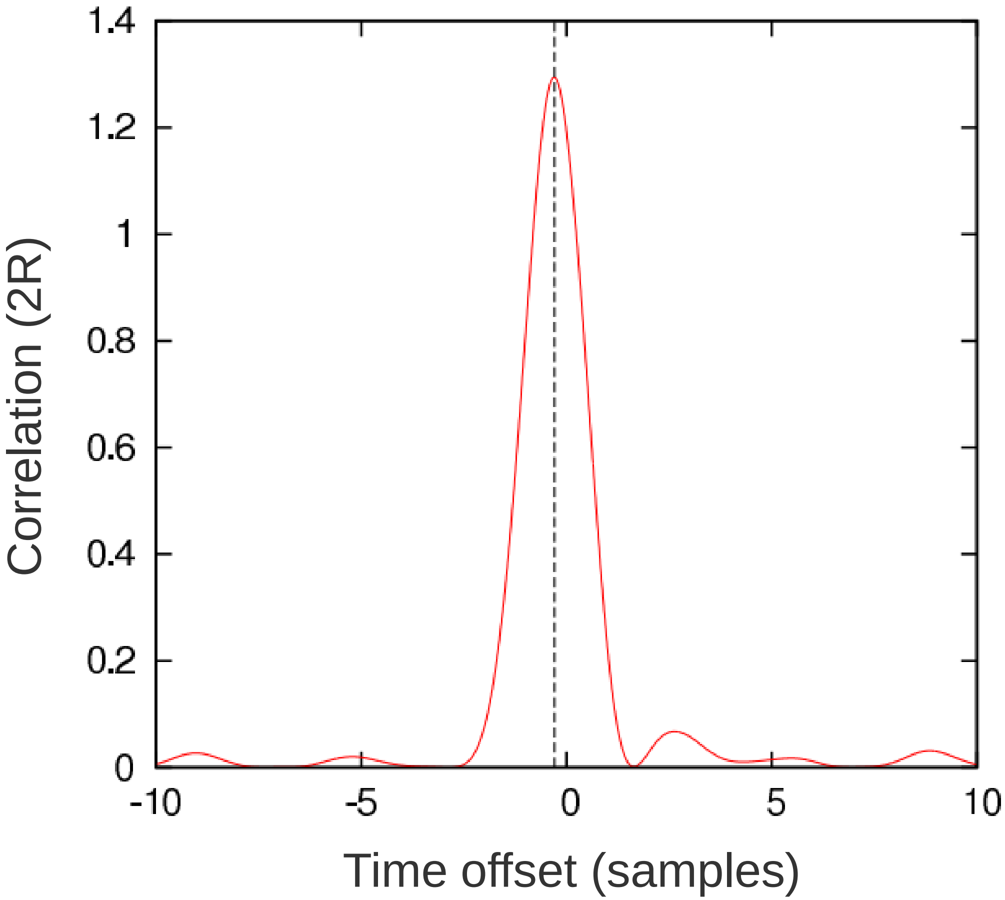
- Known function of continuous Barker code
- Thus, simulation of "samplings" at suboptimal time offsets possible.
- Can be pre-calculated.
- Comparison of *simulated* samples to *observed* samples.

Subsample Precision Method - Simulated Samplings of Continuous Barker Code



- Comparison using correlation function

Subsample Precision Method – Finding the Maximum Correlation Point

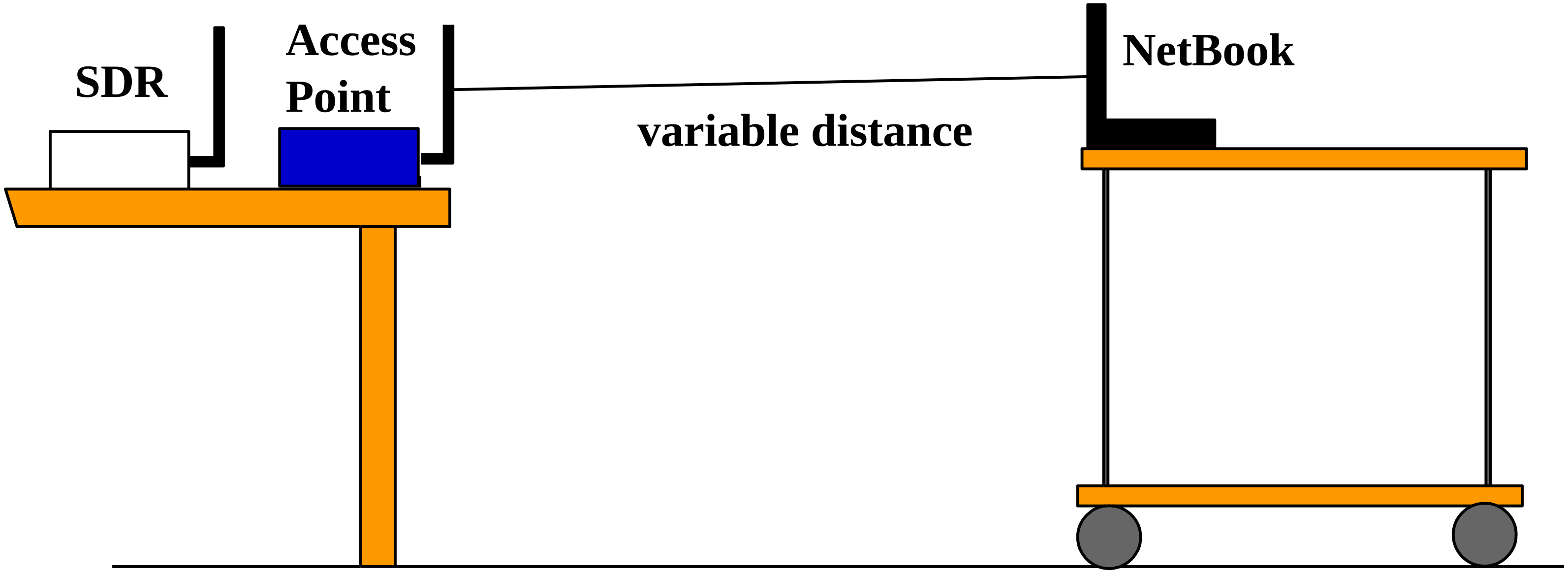


- "Real" observed samples
- Correlation at different time offsets
- Clear Optimum at -0.295 samples

Better time stamping? Ok… But how well did it actually perform?

PERFORMANCE EVALUATION

Evaluation Setup

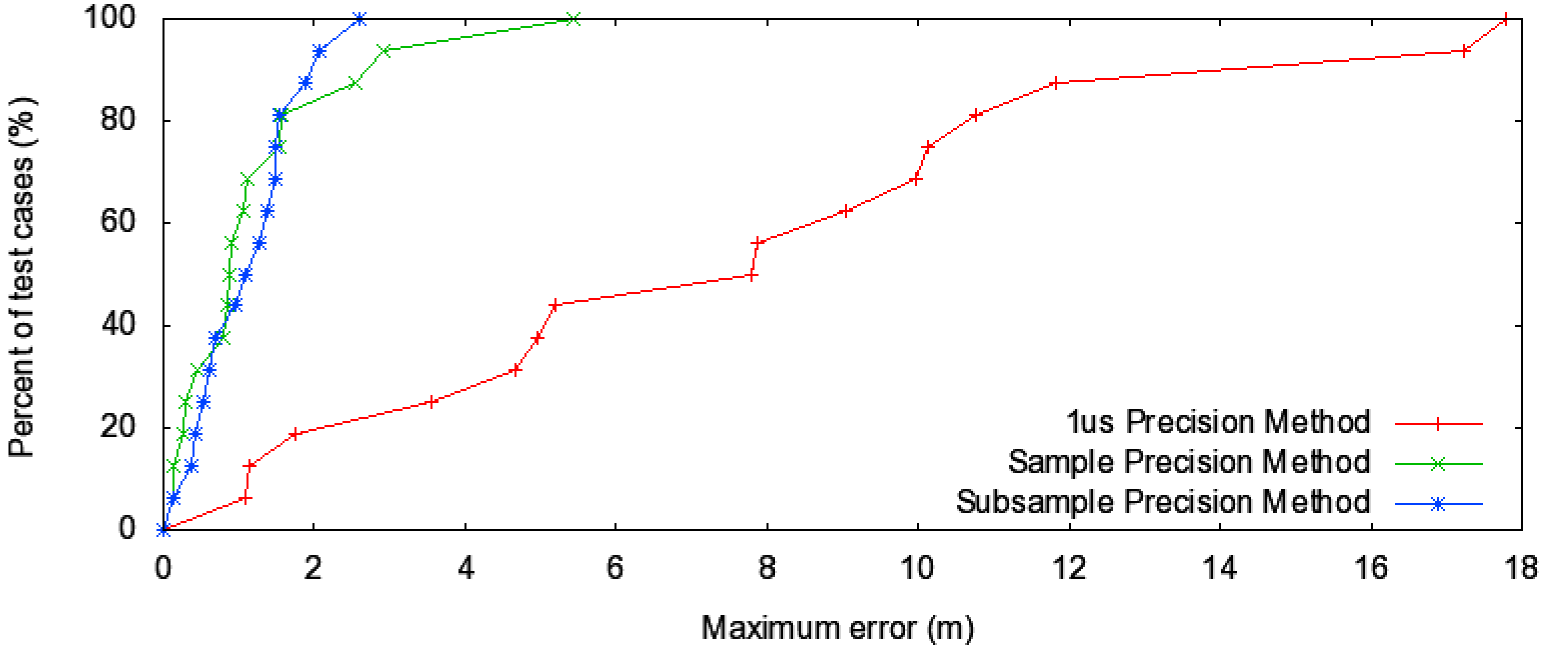


Infrastructure
- Access Point (off-the-shelf)
- Monitor device (SDR)

Mobile part
- Localization target (netbook)

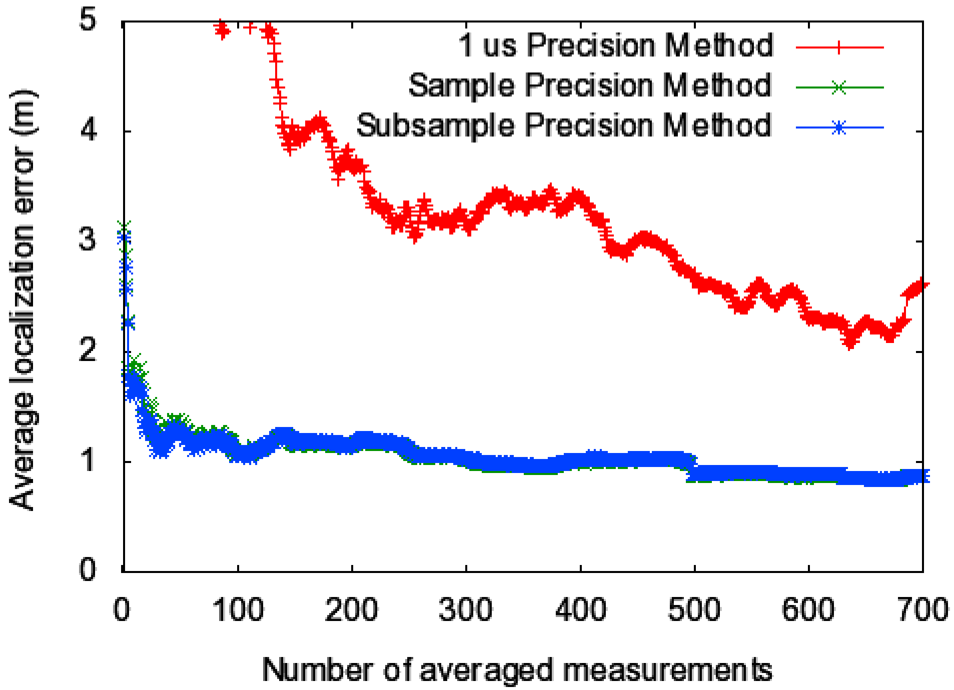
- SDR recorded samples to disk
- Different methods applied to same observations (= recordings)

Cumulative Error Distribution (30 Frame Sequences)



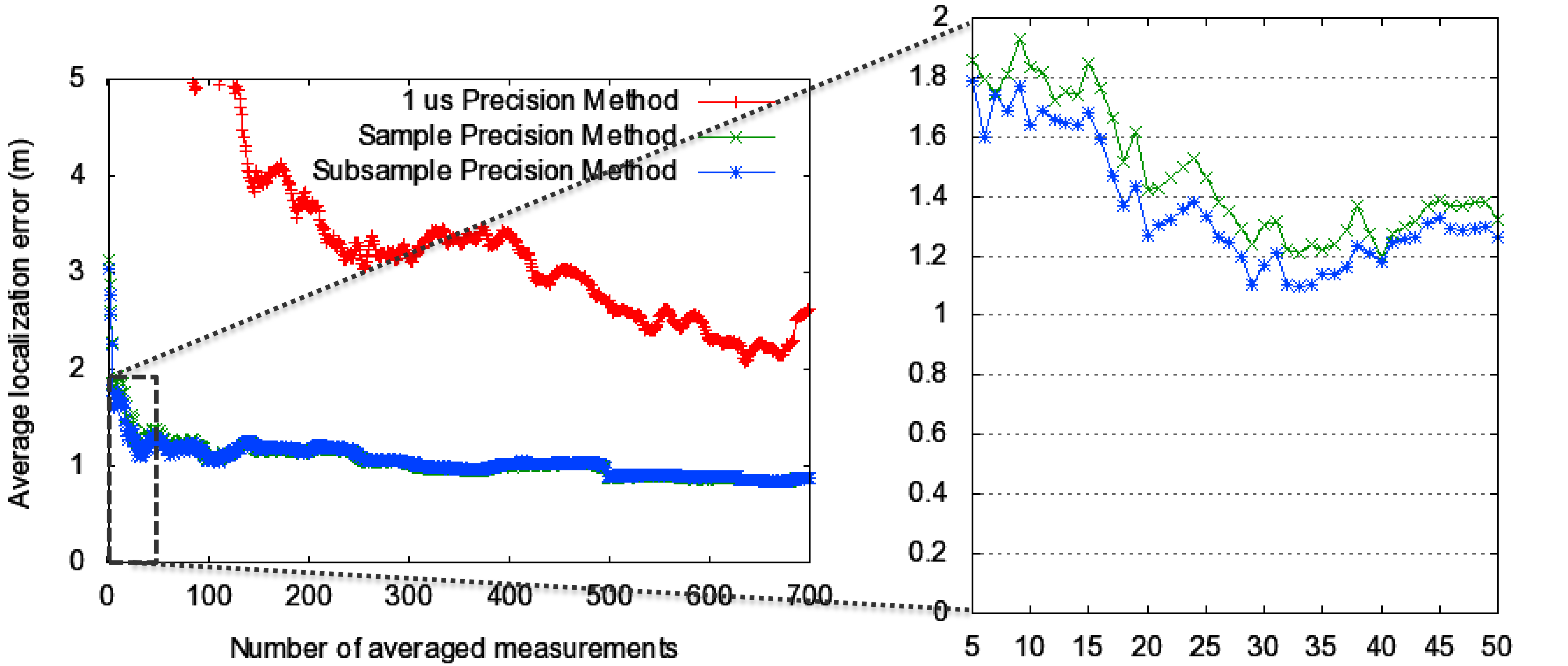
Method	Average	Worst case
1 µs Precision Method	7.80 m	17.80 m
Sample Precision Method	1.30 m	5.43 m
Subsample Precision Method	1.17 m	2.60 m

Average Error vs. Number of Measurements



Method	Notes
1 µs Precision Method	Much worse!
Sample Precision Method	Better than 1µs Precision Method
Subsample Precision Method	Better than Sample Precision Method at fewer measurement samples

Average Error vs. Number of Measurements



Method	Notes
1 µs Precision Method	Much worse!
Sample Precision Method	Better than 1µs Precision Method
Subsample Precision Method	Better than Sample Precision Method at fewer measurement samples

What can we derive from that?

SUMMARY & CONCLUSIONS…

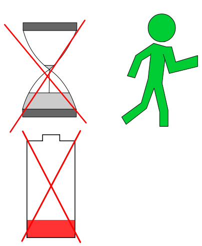
Summary & Conclusions

We improved overall accuracy

Method	Average	Worst case
1 µs Precision Method	7.80 m	17.80 m
Sample Precision Method	1.30 m	5.43 m
Subsample Precision Method	**1.17 m**	**2.60 m**

We minimized costs

- Existing infrastructure
- Only one SDR for multiple stationary nodes



Measuring 30 frame sequences enough

- Faster localization
- Improved tracking of moving objects
- Reduced energy consumption

Thanks for your interest and your feedback…

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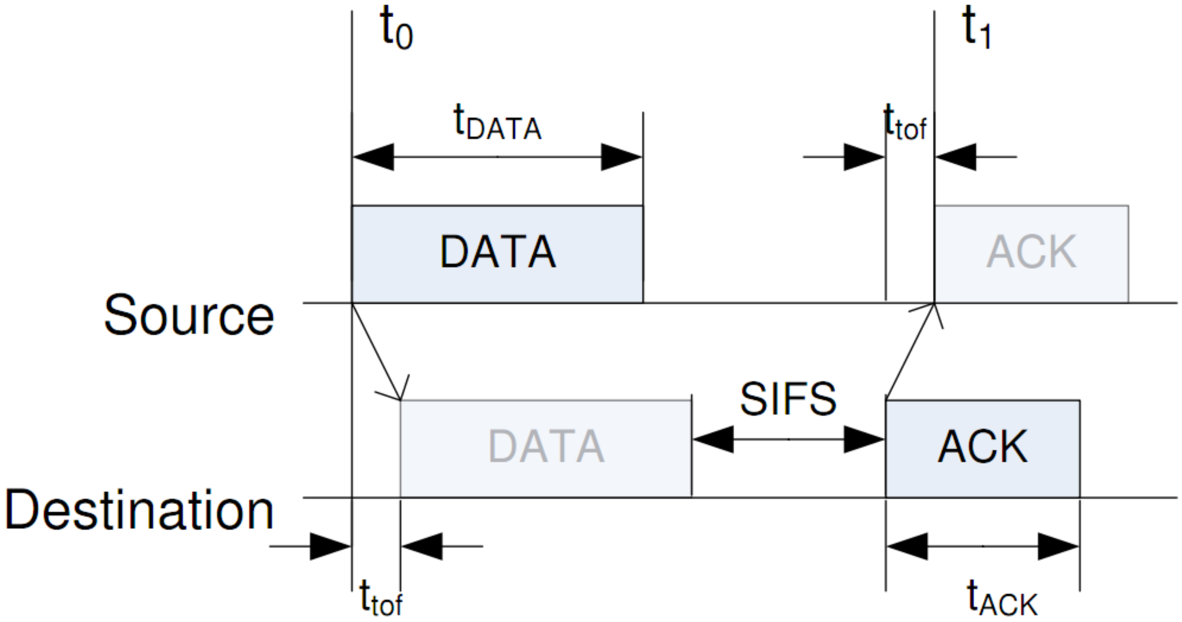
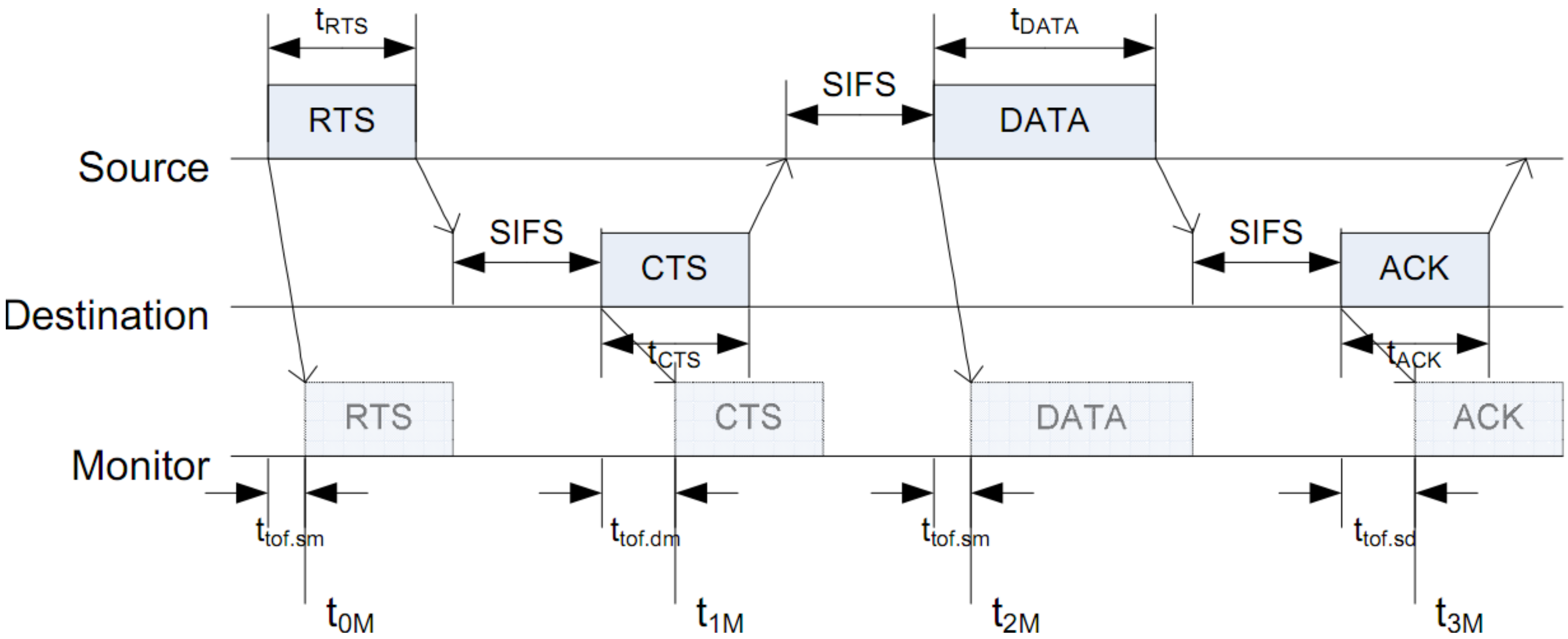
Two-Way Time of Flight Measurements



Indirect Four-Way Time of Flight Measurements



$$t_{tof} = \frac{1}{2}(t_{2M} - t_{0M} - 2t_{SIFS} - t_{CTS} - t_{RTS})$$

$$t_{tof} = \frac{1}{2}(t_{3M} - t_{1M} - 2t_{SIFS} - t_{DATA} - t_{CTS})$$