

Advancing Wireless Link Signatures for Location Distinction



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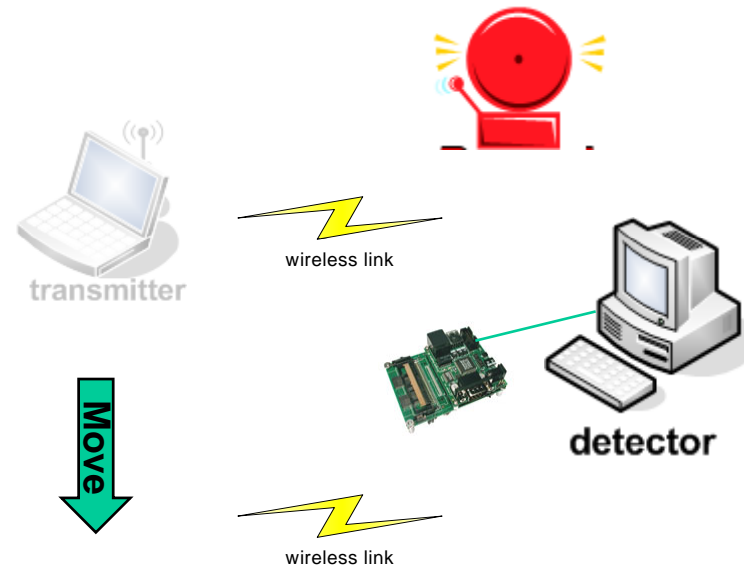
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Location Distinction

- ability to know when a device has changed position
- unlike localization, no location estimation
- applications
 - monitoring
 - trigger for localization
 - location based authentication



Our Goal

location distinction based on unique measurable wireless link characteristics, or link signatures

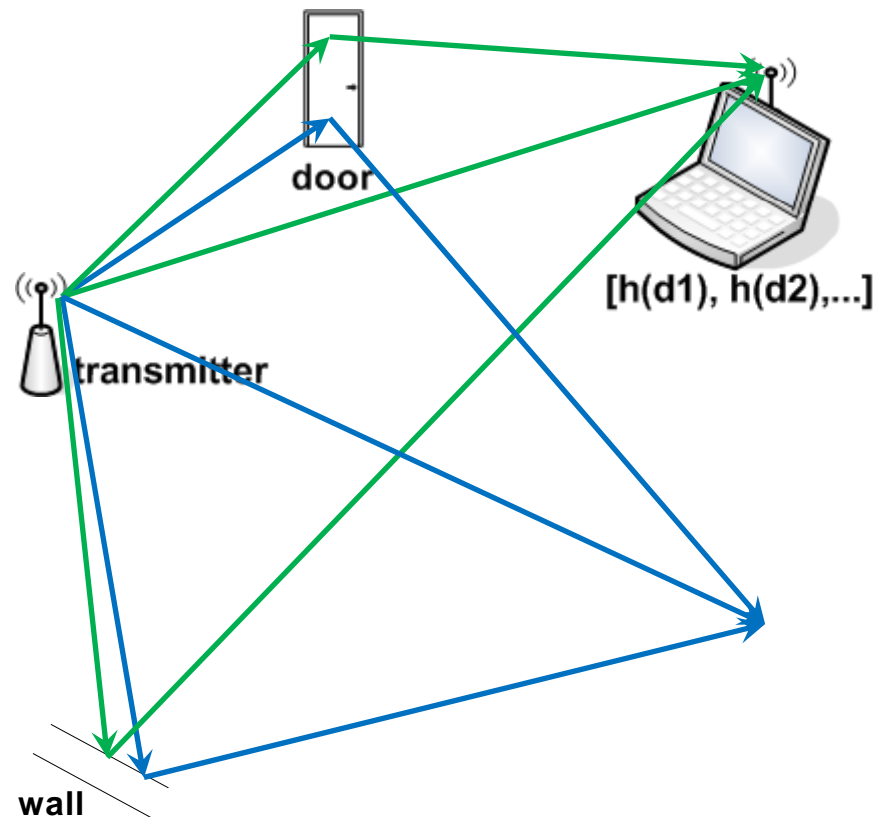
Temporal Link Signature

[Patwari, Kasera 07]

- magnitude of channel impulse response
- essentially superposition of multipath
- signature:

$$\mathbf{h}^{(n)} = [|h^{(n)}(0)|, \dots, |h^{(n)}(N)|]^T$$

- keep history of signatures



Temporal Link Signature (contd.)

- distance between signatures

$$\|\mathbf{h}^{(n)} - \mathbf{h}^{(m)}\|_{\ell 2}$$

- compare new signature with history, detect location change if distance greater than threshold

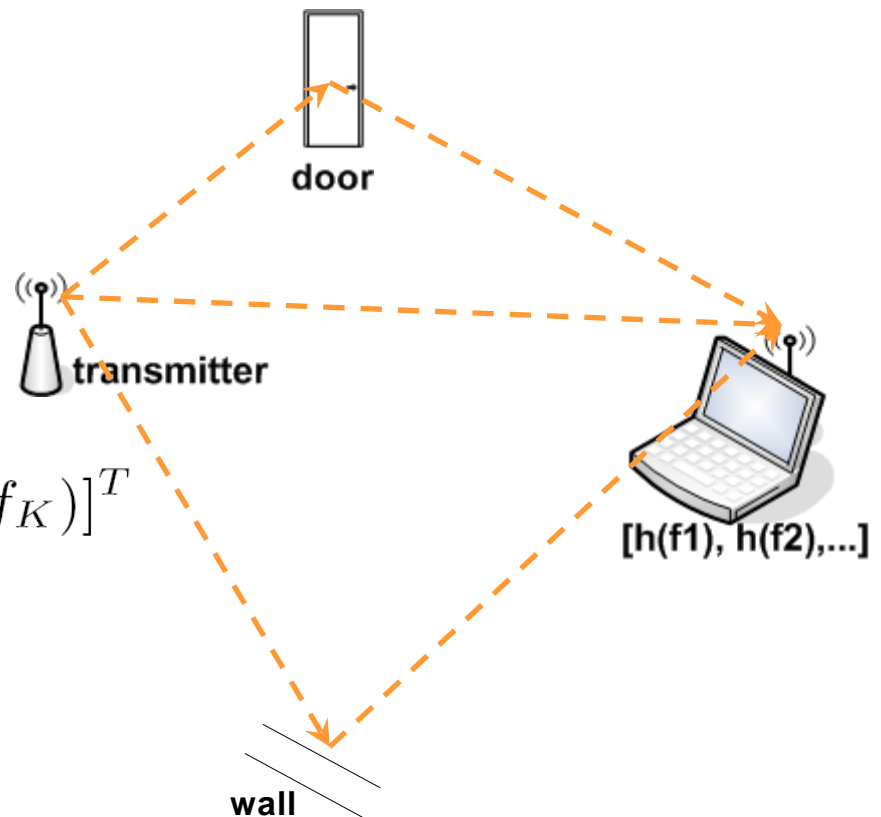
Multiple Tone Signature

[Li et al 06]

- multiple carrier waves or tones simultaneously transmitted to receiver
- measure complex frequency response of each tone
- signature:

$$\mathbf{h}^{(n)} = [H^{(n)}(f_1), \dots, H^{(n)}(f_K)]^T$$

- keep history of signatures



Multiple Tone Signature (contd.)

- correlation between signatures

- original

$$\frac{\sum_{\kappa} H^{(n)}(f_{\kappa}) H^{(m)}(f_{\kappa})^*}{\|\mathbf{h}^{(n)}\|^2}$$

- our refinement

$$\frac{\sum_{\kappa} H^{(n)}(f_{\kappa}) H^{(m)}(f_{\kappa})^*}{\|\mathbf{h}^{(n)}\| \|\mathbf{h}^{(m)}\|}$$

- compare new signature with history, detect location change if correlation less than threshold

Overview

- qualitative comparison of two signatures
- develop new signature
- performance comparison
- temporal behavior study
- summary

Qualitative Comparison

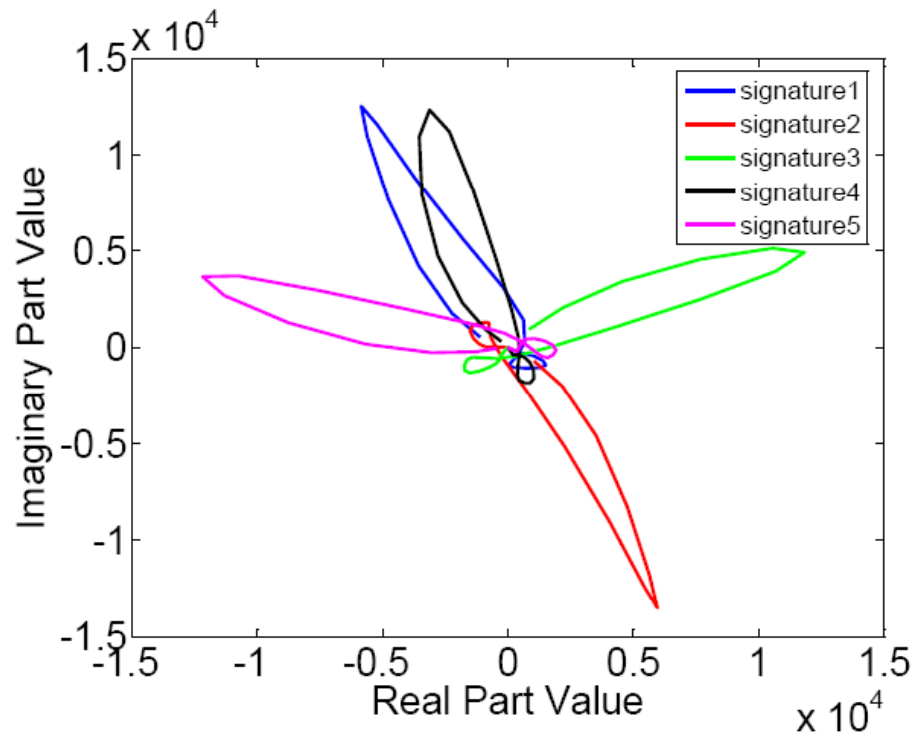
- both measure multipath to identify links
- temporal CIR signature
 - multipath orthogonal in time domain
 - phase change of one path affects only small portion of signature
 - robust against small changes in multipath
- multiple tone signature
 - phase preserved in complex-valued response
 - phase change of one path affects every frequency response

Advancement: Complex Temporal Signature

- complex channel impulse response
- signature:
$$\mathbf{h}^{(n)} = [h^{(n)}(0), \dots, h^{(n)}(N)]^T$$
- combines best features
 - robust to small changes in multipath
 - preserves phase information
- however, ...

Undesirable Phase Changes

- received signal phase: $\varphi + 2\pi f t$
- imperfect clock synchronization, $2\pi f \Delta t$
- differences in carrier frequency, $2\pi \Delta f t$



same link, different signatures

Change in Distance Metric

- to cope with undesired phase changes
- intuition: rotate one signature to align with other

$$\|\mathbf{g} - \mathbf{h}\|_{\phi_2}^2 = \min_{\phi \in (0, 2\pi)} \|\mathbf{g}e^{j\phi} - \mathbf{h}\|_{\ell_2}^2$$

- new ϕ_2 metric:

$$\|\mathbf{g} - \mathbf{h}\|_{\phi_2}^2 = \|\mathbf{g}\|^2 + \|\mathbf{h}\|^2 - 2\|\mathbf{g}^* \mathbf{h}\|$$

Measurement Based Evaluation

- data from [Patwari, Kasera 07]
- 9000 measurements in office environment, after hours
- DSSS signal with 40 MHz chip rate, 1024 code-length, central frequency 2443 MHz

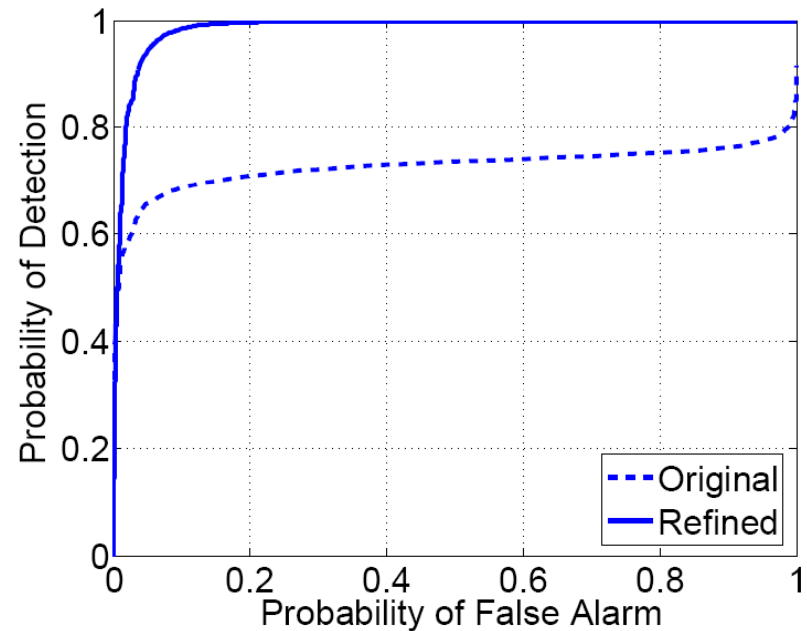
Multiple Tone Correlation Refinement

- Original correlation

$$\frac{\sum_{\kappa} H^{(n)}(f_{\kappa})H^{(m)}(f_{\kappa})^*}{\|\mathbf{h}^{(n)}\|^2}$$

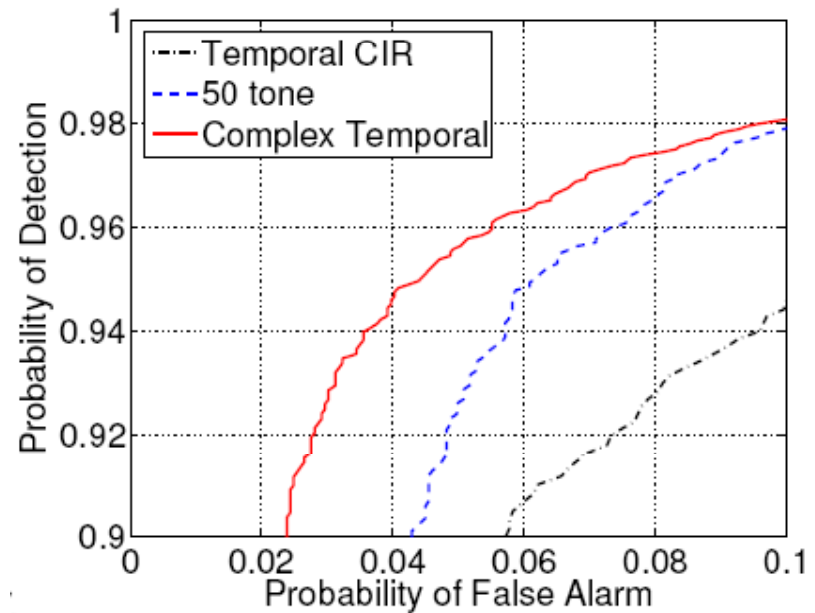
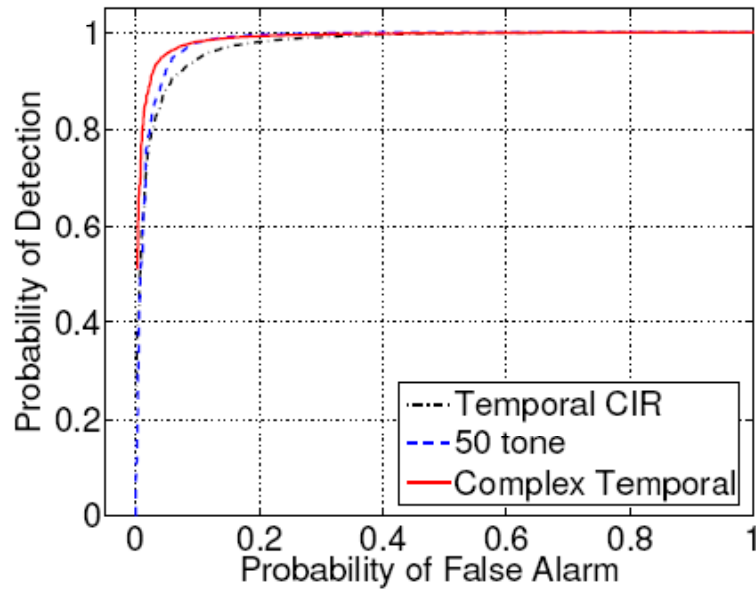
- Our refinement

$$\frac{\sum_{\kappa} H^{(n)}(f_{\kappa})H^{(m)}(f_{\kappa})^*}{\|\mathbf{h}^{(n)}\| \|\mathbf{h}^{(m)}\|}$$



Significant increase in probability of detection

Comparison of Three Signatures



complex temporal signature

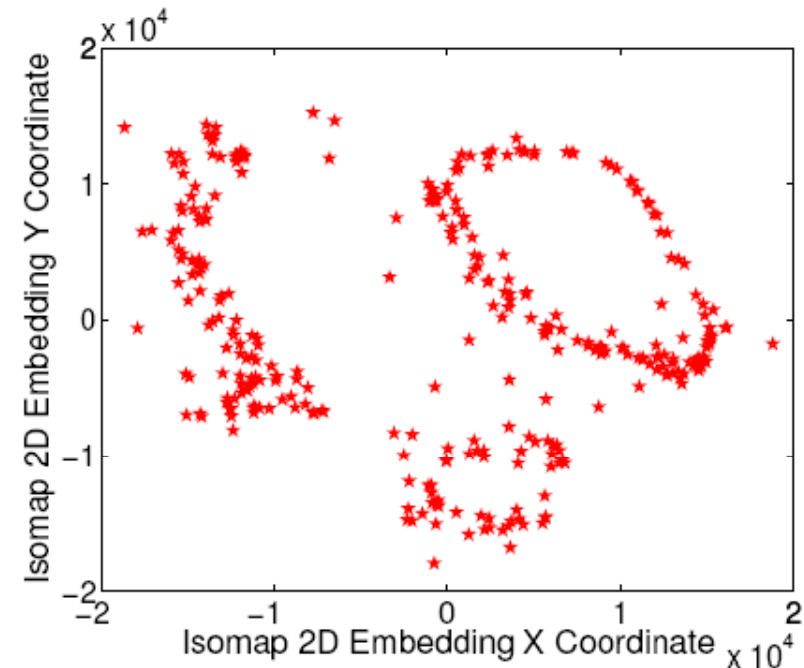
- outperforms existing ones
- performs especially well at low false alarm rates

Temporal Behavior of Signatures

- external factors affect signatures of a link over time
 - can cause high false alarms
- previous measurement done in static environment (after hours)
- new measurement campaign
 - measurements taken during work hours
 - four Tx/Rx location pairs to obtain data under temporally varying conditions

Modeling Temporal Behavior

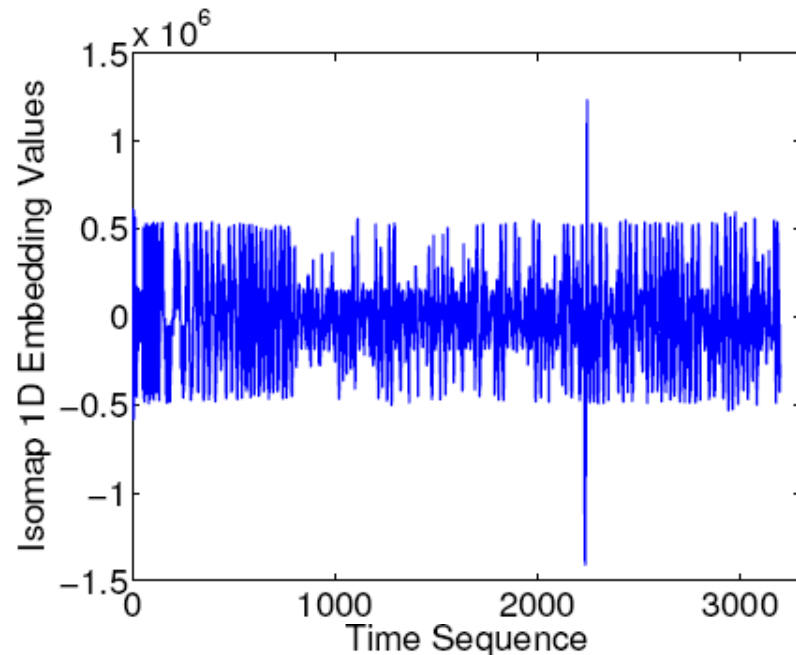
- use non-linear dimensionality reduction
- reduced 100D signatures to just 1D or 2D



- 2D embedding example
- signatures fall into different groups

Markov Model of Signatures

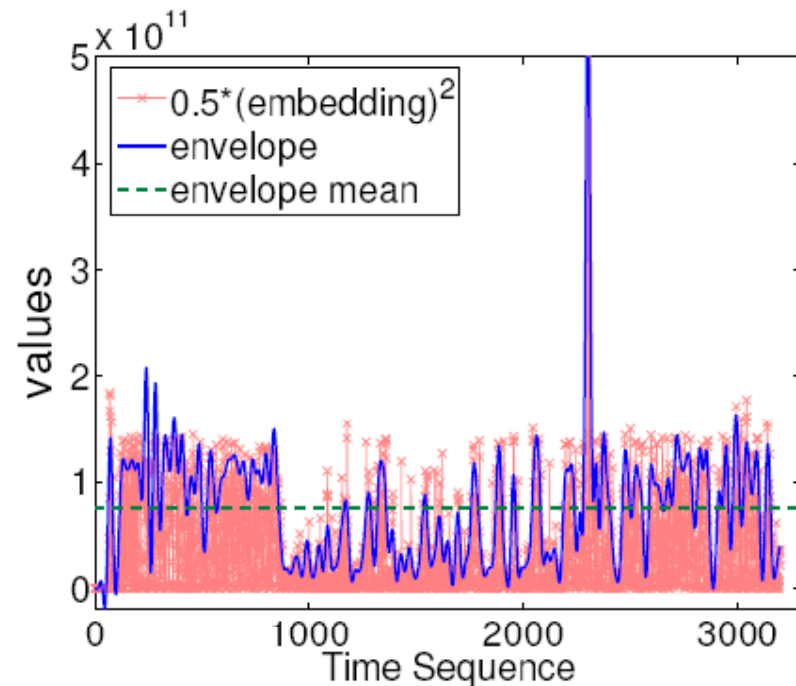
- model each group of link signatures as a state in Markov chain
- how to find probabilities of state transition?



- 1D embedding example
- state transitions from amplitude changes

Extract Transition Probabilities

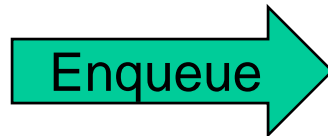
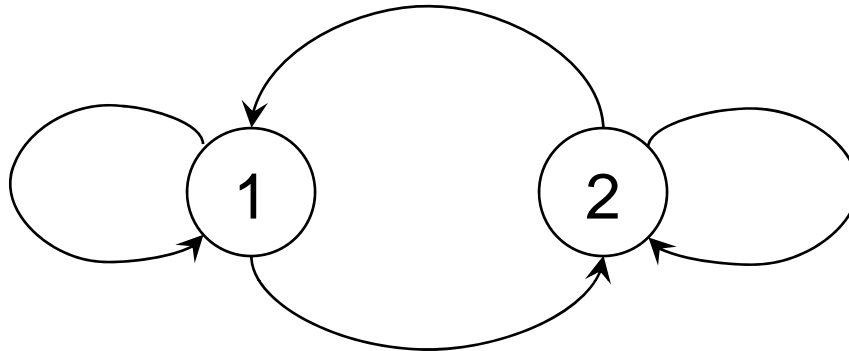
- treat 1D embedding as *AM* signal
- pass squared signal through low-pass filter to track envelope
- set threshold to detect transitions



Incorporating Temporal Model

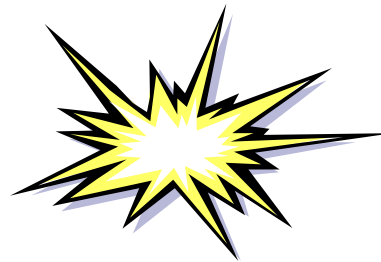
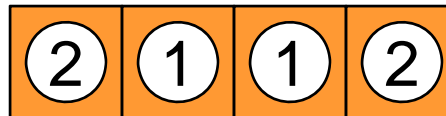
- **Goal:** reducing false alarms due to temporal variation in link signatures
- a new buffer replacement policy
 - before: single FIFO for signature history, length B
 - advancement: one FIFO each for K states of Markov chain, length B/K

Original Buffer Replacement Policy



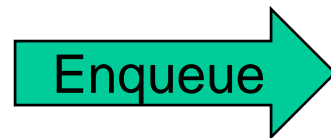
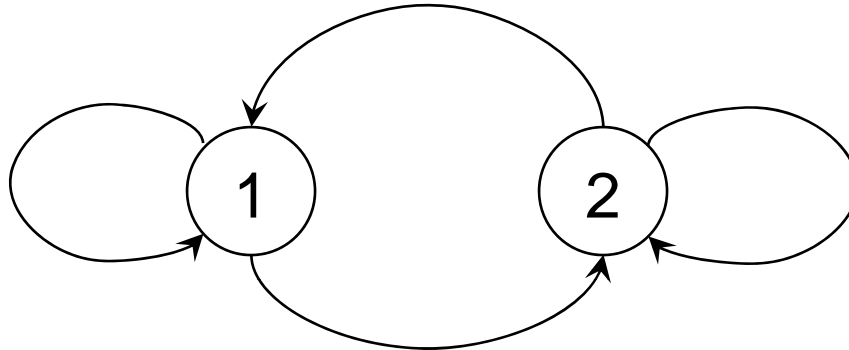
A single FIFO buffer of size B, B=4

②



Different State
False Alarm
(DSFA)

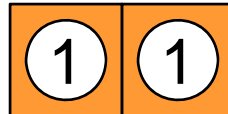
New Buffer Replacement Policy



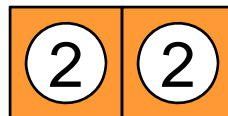
K separate FIFO buffers, each with size B/K . $B=4$, $K=2$ in this example.



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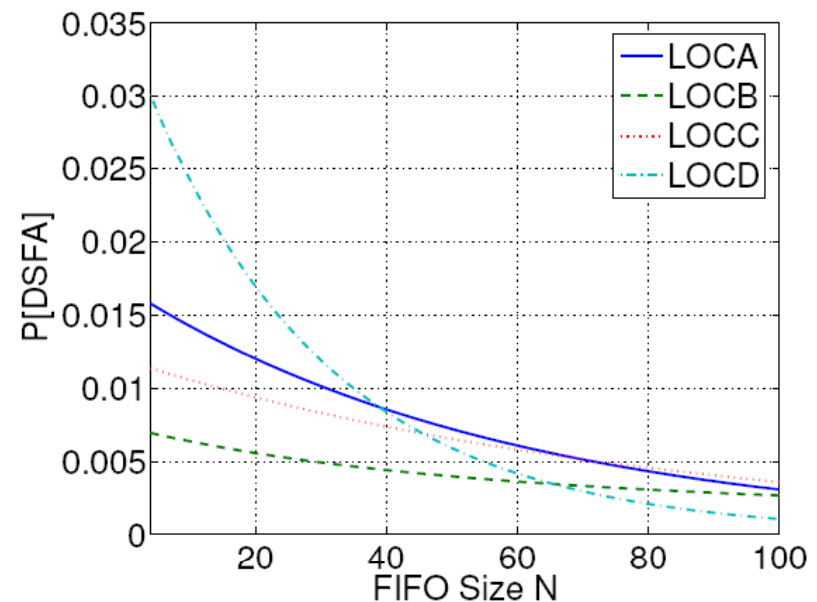


②



Original Buffer P[DSFA]

- decreases exponentially with length of history
- new buffer policy removes these false alarms



Conclusions

- compared existing multipath-based link signatures
- developed a new link signature that outperforms existing ones
- modeled the temporal behavior of link signatures
- reduced false alarms in location distinction

Thank You

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Visit <http://www.cs.utah.edu/~junxing> for more information

BACKUP SLIDES

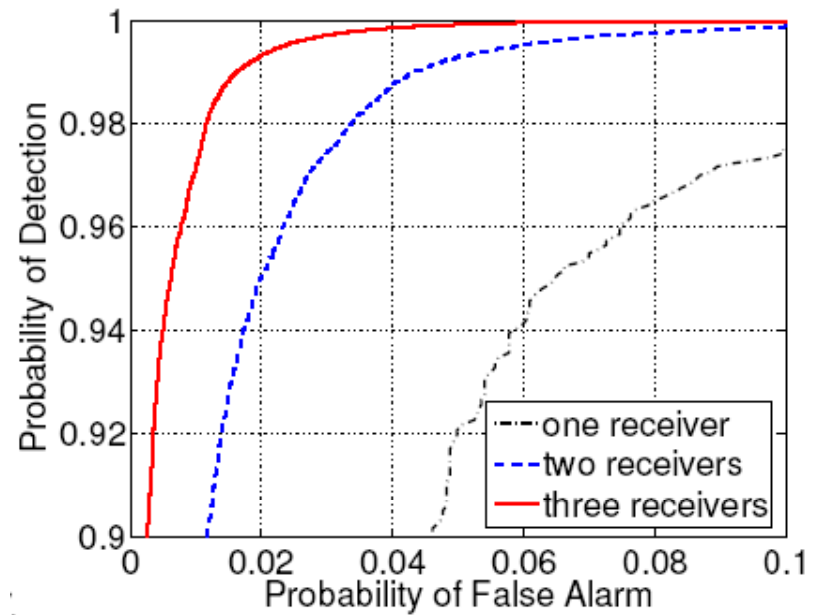
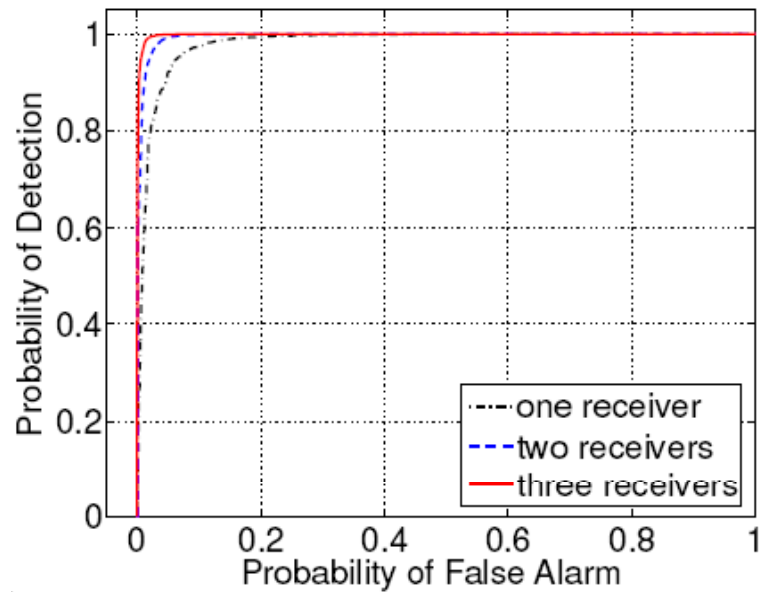
Multipath Channel Response

- Wireless channel consists of multiple paths caused by reflections, diffractions, and scattering of radio waves
- When sending $s(t)$ through channel, receiver receives:

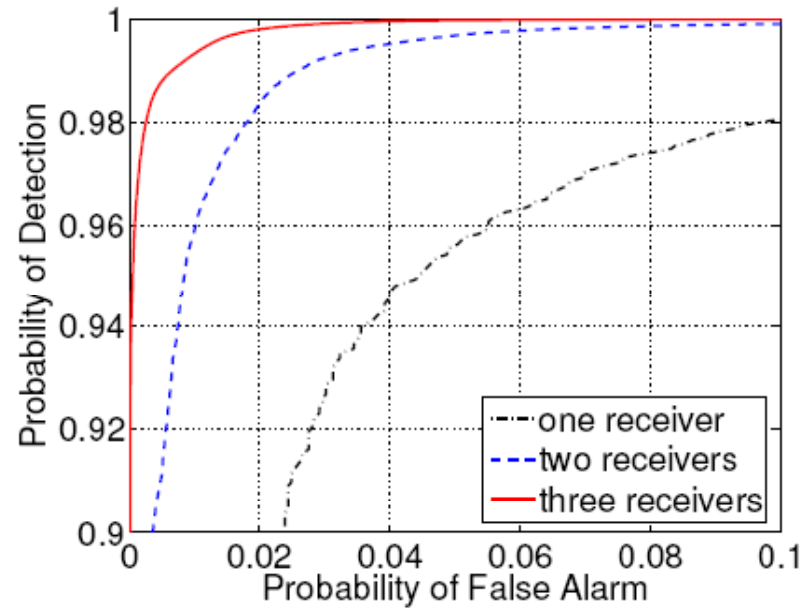
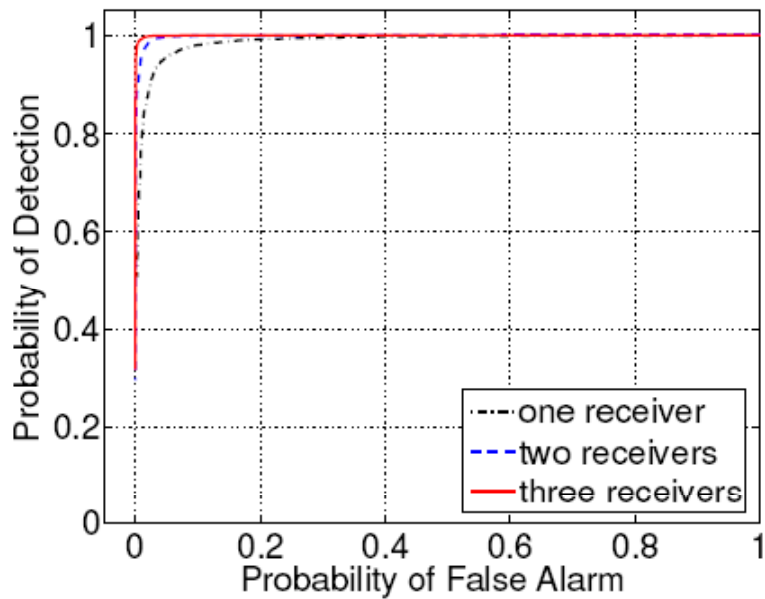
$$r(t) = s(t) * h(t) = \sum_{l=1}^L \alpha_l e^{j\phi_l} s(t - \tau_l) \quad h(\tau) = \sum_{l=1}^L \alpha_l e^{j\phi_l} \delta(\tau - \tau_l)$$

- Channel Impulse Response: channel response in the time domain - $h(t)$
- Channel Frequency Response: channel response in the frequency domain - $H(f)$

Evaluation: Multiple Receiver Refined Metric



Evaluation: Multiple Receiver Complex Temporal Signature



K > 2 State Markov Chains

- Hitting time:

$$T_i = \min_{n>0} \{X_n = i | X_0 = i\} \quad E[T_i] = 1/\pi_i$$

- When hitting time is longer than N, we will have DSFA error
- Assuming tail of the probability mass function T is geometric, for large N:

$$P[T_i > N] = (1 - \pi_i)^{N+1}$$

- Probability of DSFA is:

$$P[DSFA] = \sum_i \pi_i P[T_i > N] \approx \sum_i \pi_i (1 - \pi_i)^{N+1}$$

Future Work

- Apply our methodology to more data
- Build system on software defined radio platform
- Continue advancing link signatures