No Training Hurdles: Fast Training-Agnostic Attacks to Infer Your Typing

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Background

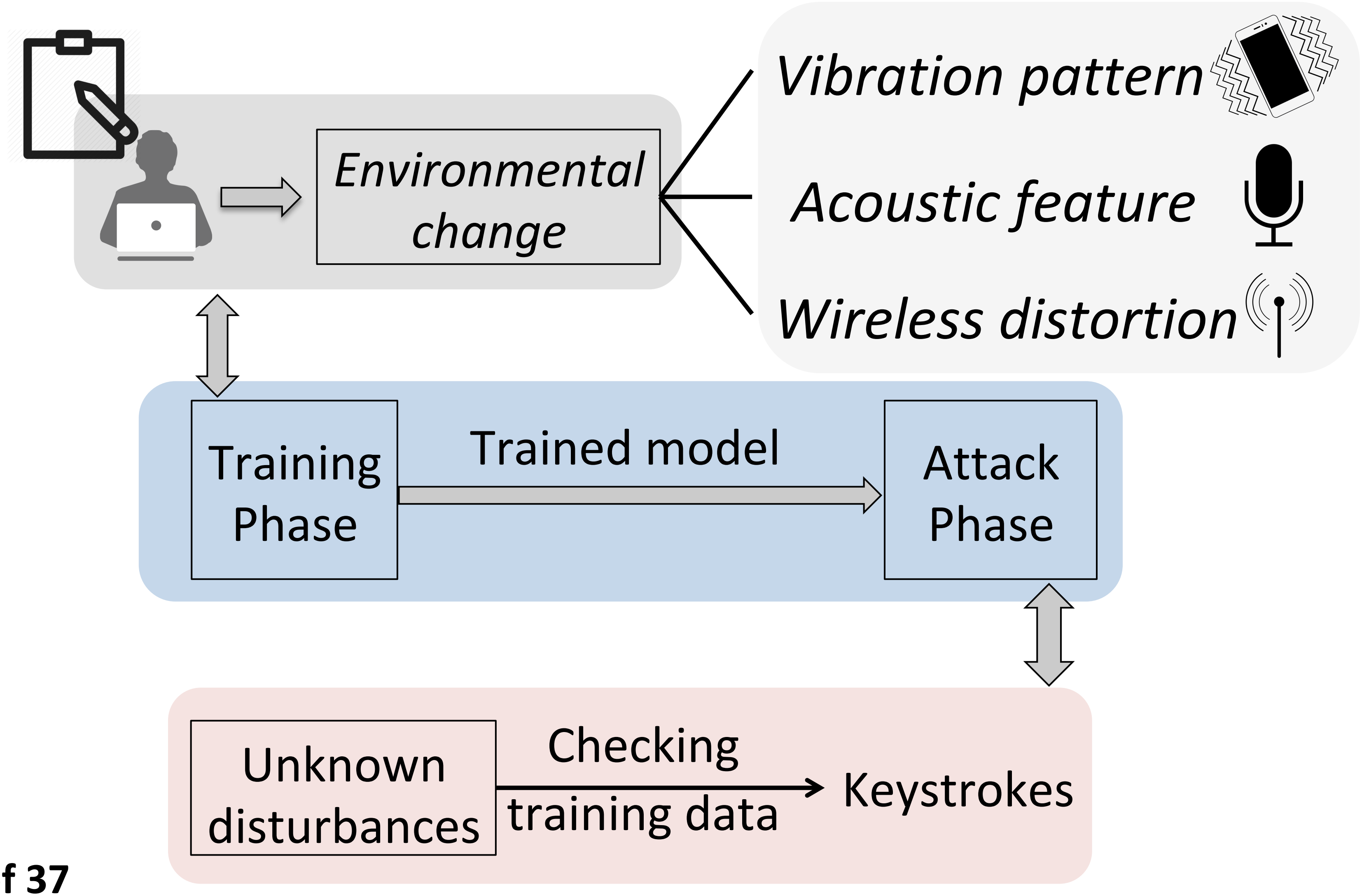
- Typing via a keyboard plays a very important role in our daily life.

Existing Non-invasive Attacks

Software or hardware based keylogger

General principle: pressing *a key* causes subtle *environmental impacts* unique to that key

Example Attacks



Environmental change

Vibration pattern

Acoustic feature

Wireless distortion

Training Phase

Trained model

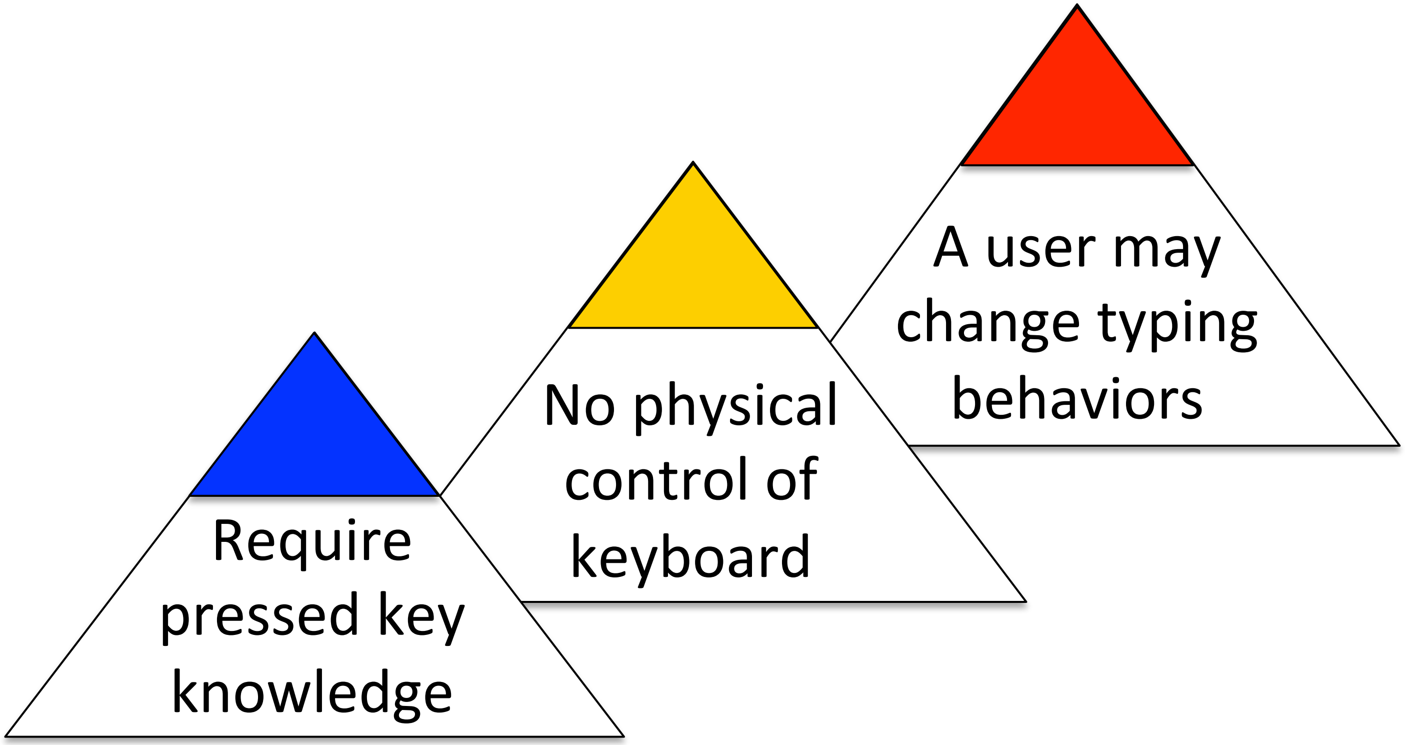
Attack Phase

Unknown disturbances

Checking training data

Keystrokes

Why Is Training A Hurdle



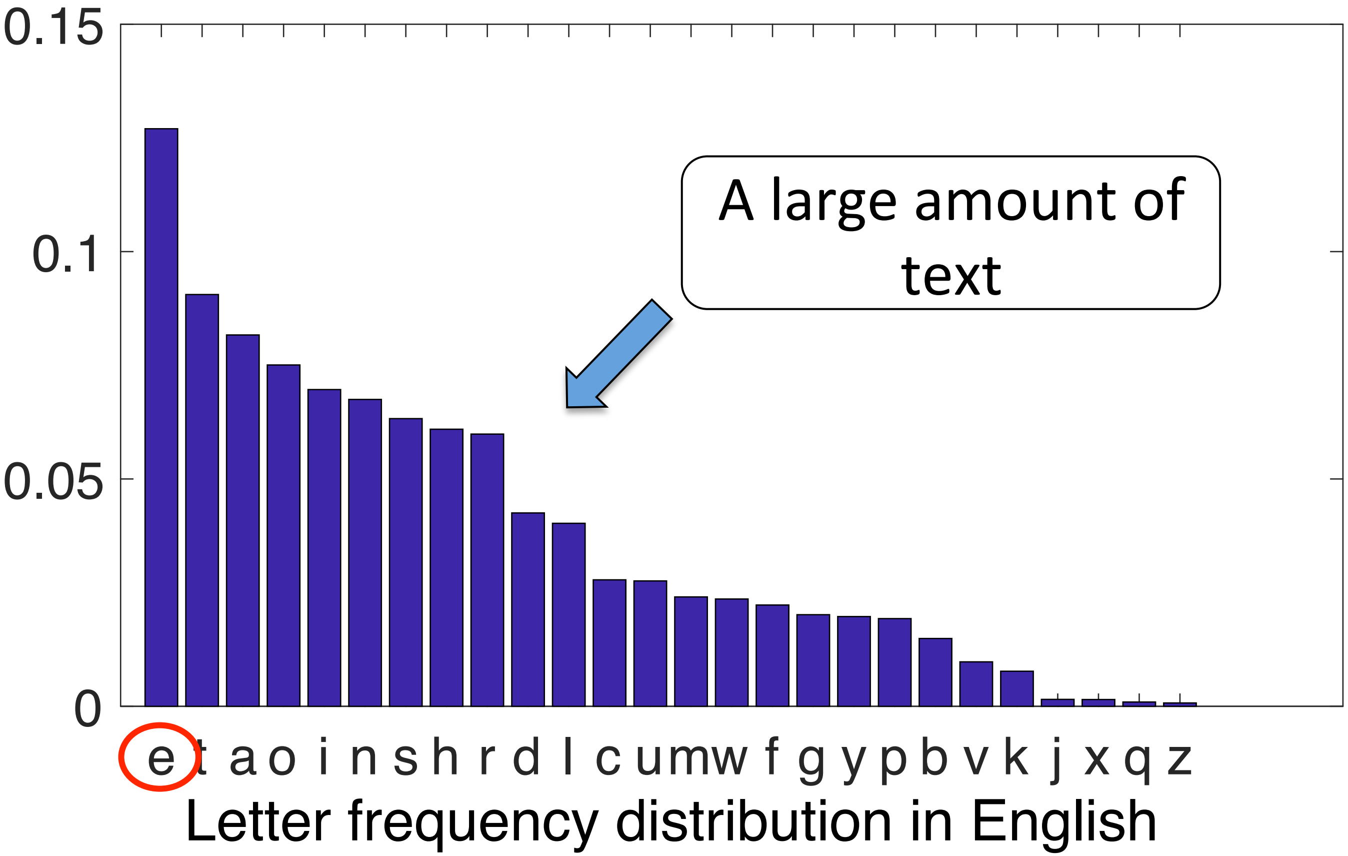
Require pressed key knowledge

No physical control of keyboard

A user may change typing behaviors

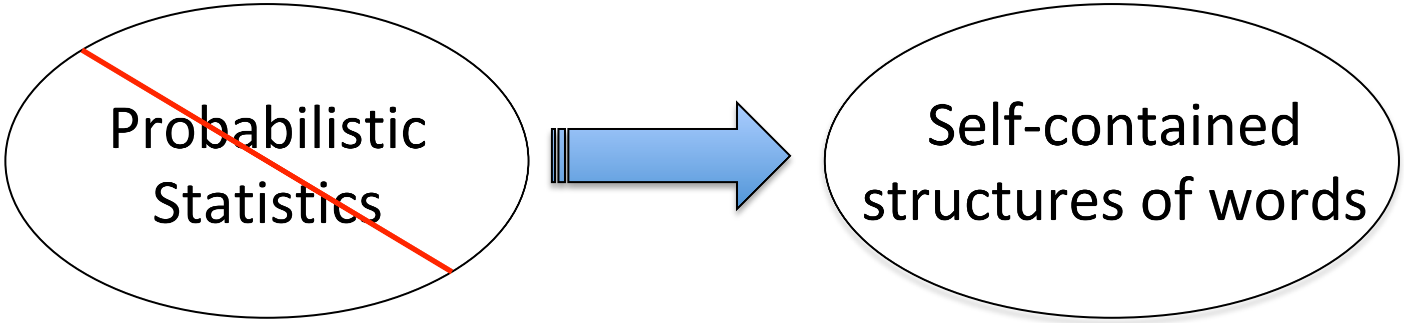
Statistical Methods

- Frequency analysis: analyzing the frequencies of observed disturbances



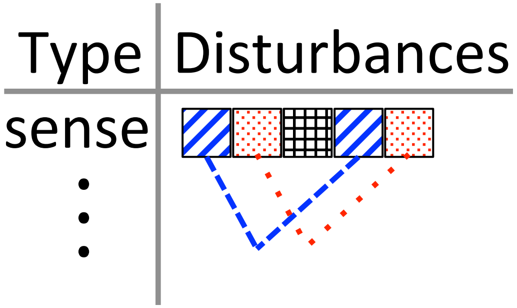
A large amount of text

Question: Is it possible to develop a non-invasive keystroke eavesdropping within a shorter time?



~~Probabilistic Statistics~~

Self-contained structures of words

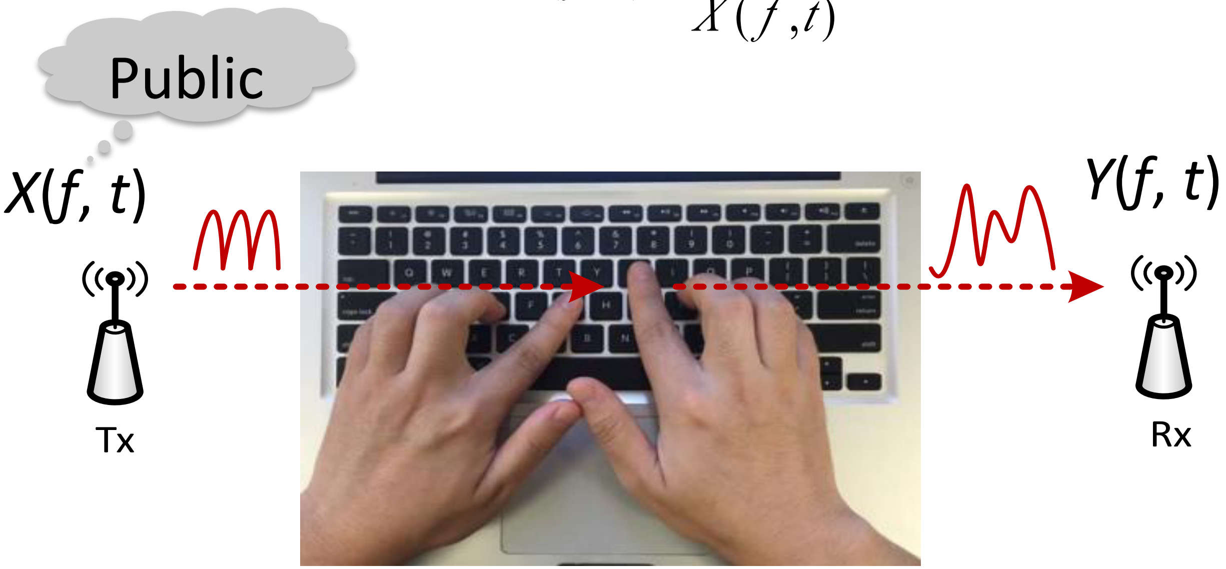


Type	Disturbances
sense	▨ ▦ ▩ ▨ ▦
⋮	

Wireless Signal Based Attacks

- Advantages:
  - ✓ Ubiquitous deployment of wireless infrastructures
  - ✓ Radio signal nature of invisibility
  - ✓ Elimination of the line-of-sight requirement
- CSI (channel state information) quantifies the disturbances

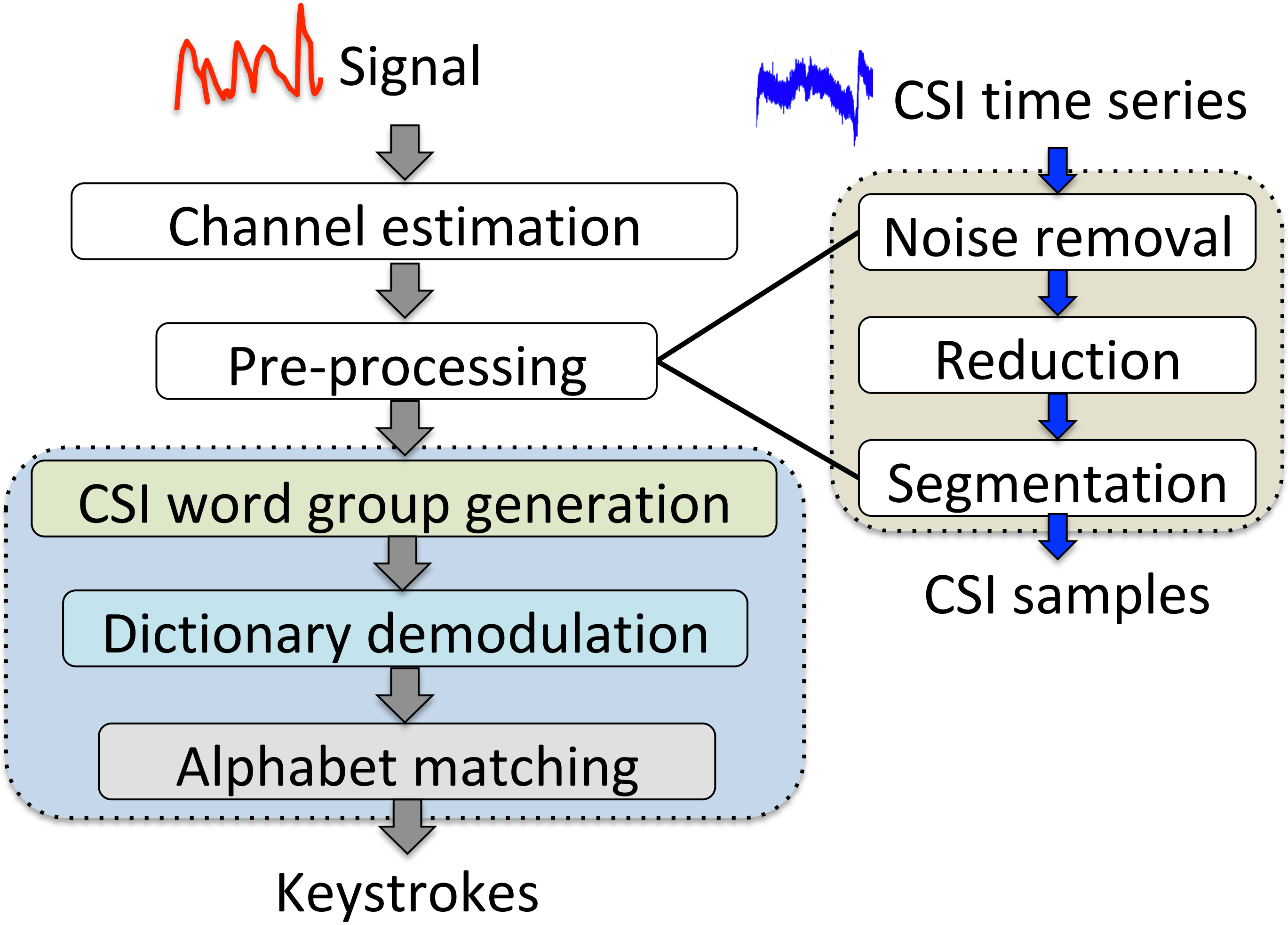
$$H(f,t) = \frac{Y(f,t)}{X(f,t)}$$



Outline

- Motivation
- Attack Design
- Experiment Results
- Conclusion

System Overview



Signal

Channel estimation

Pre-processing

CSI word group generation

Dictionary demodulation

Alphabet matching

Keystrokes

CSI time series

Noise removal

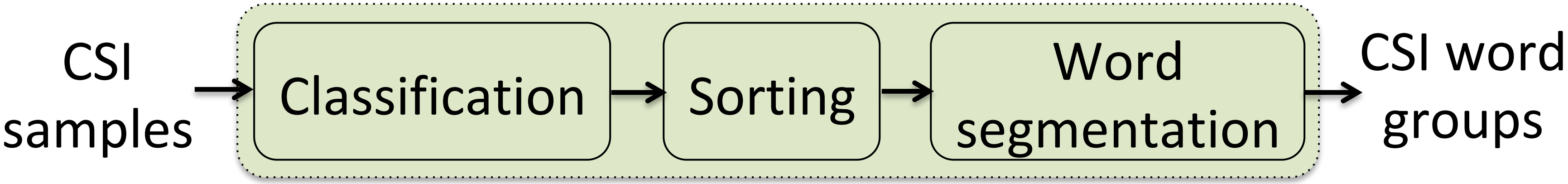
Reduction

Segmentation

CSI samples

A ***CSI sample*** refers to an individual segment corresponding to the action of pressing a key.

CSI Word Group Generation



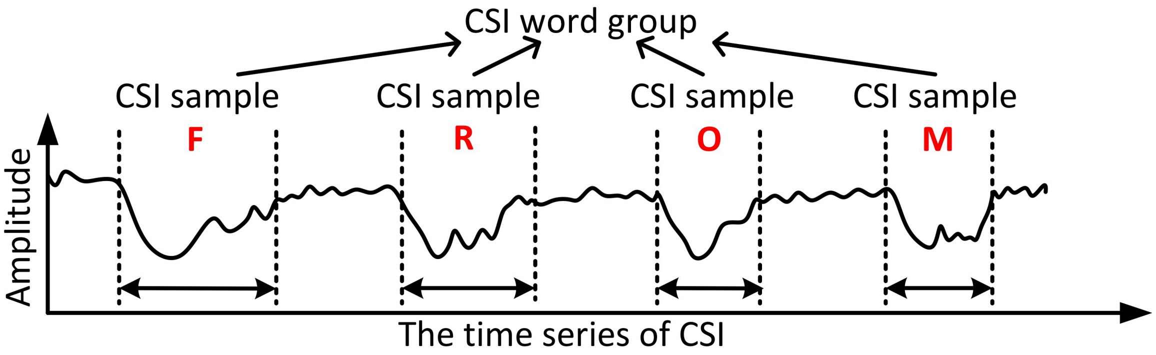
CSI samples

Classification

Sorting

Word segmentation

CSI word groups

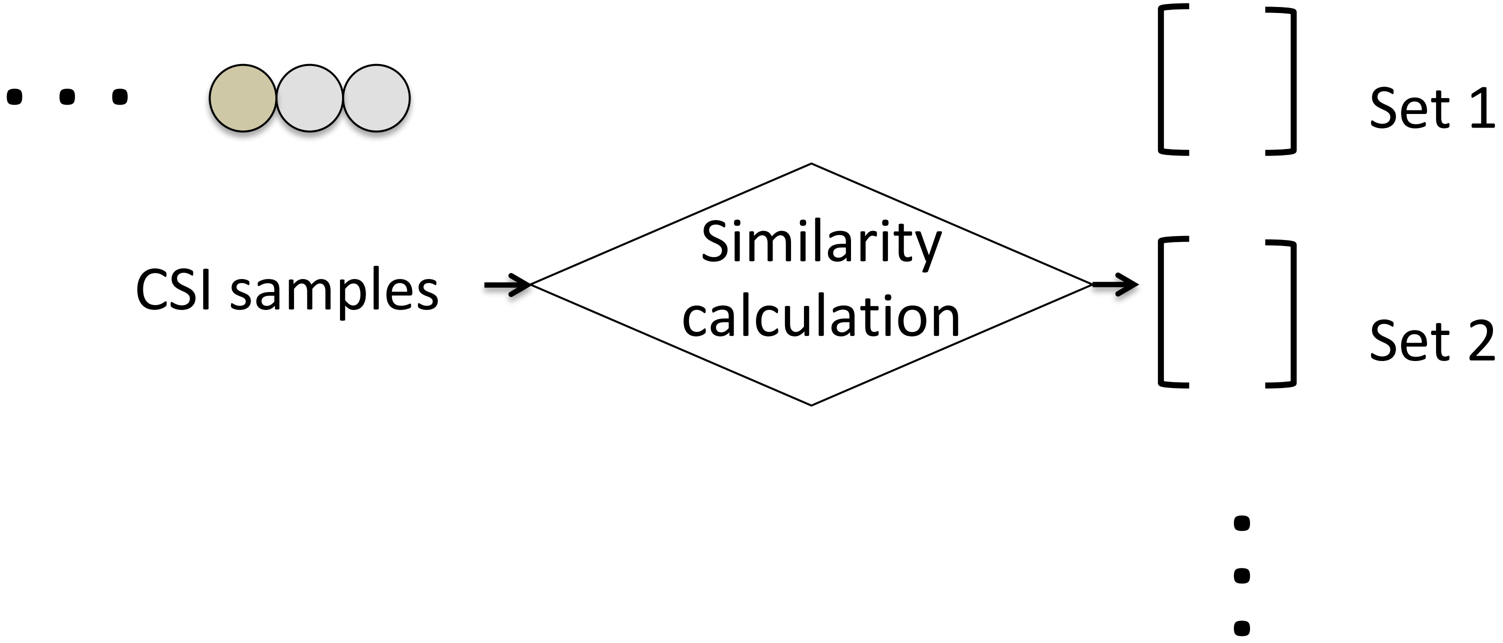


A ***CSI word group*** refers to the a group of CSI samples comprising each typed word.

Classification

Sorting

Word segmentation



CSI samples

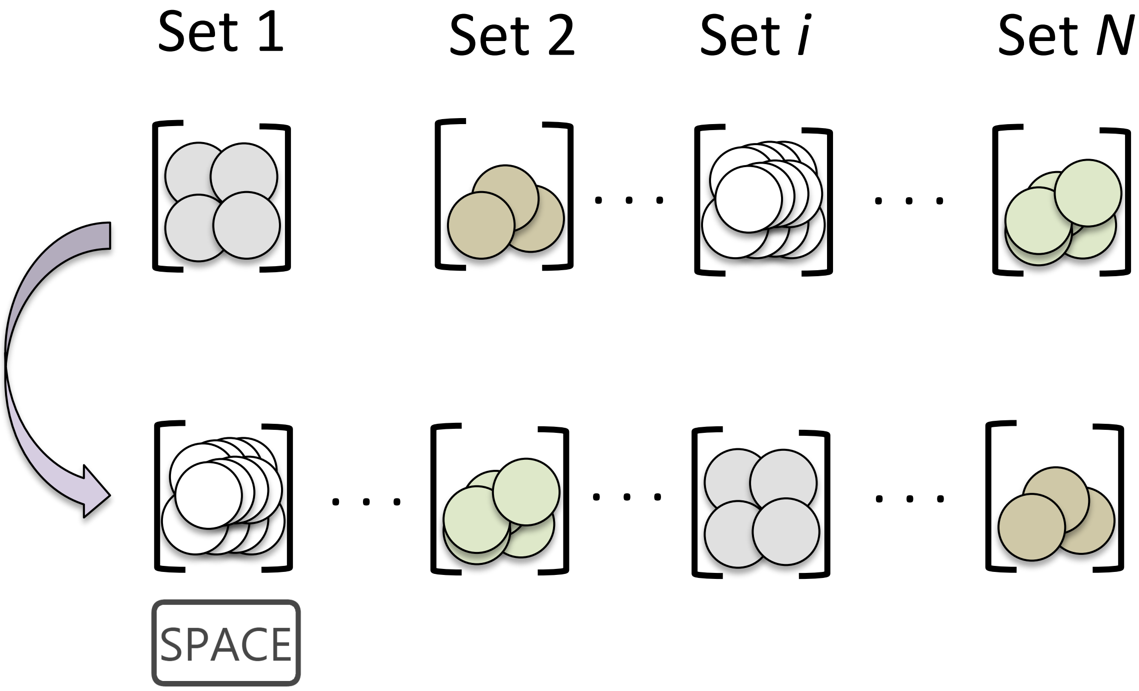
Similarity calculation

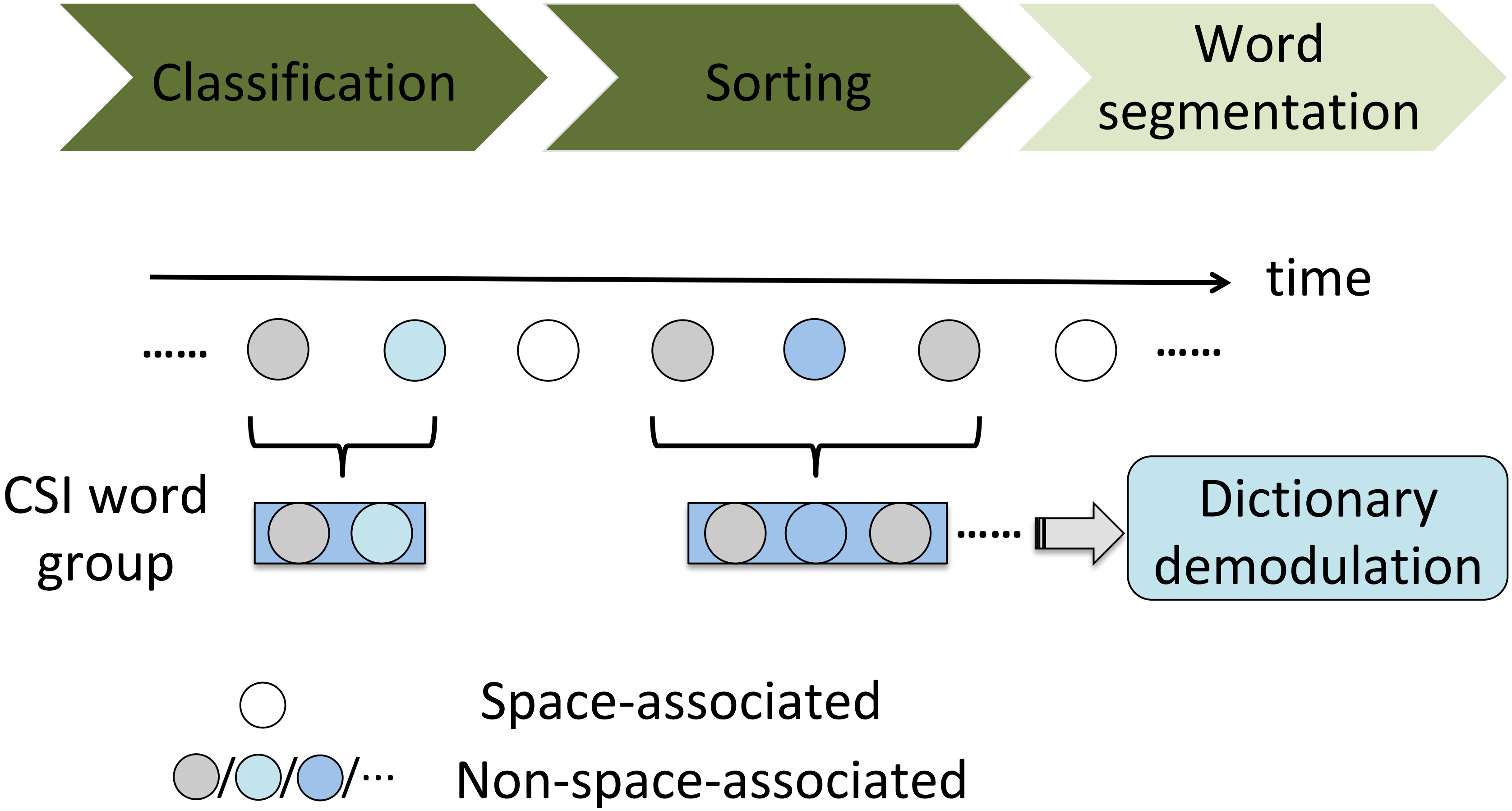
Set 1

Set 2

Classification → Sorting → Word segmentation

Sort based on the ***size***





Classification

Sorting

Word segmentation

time

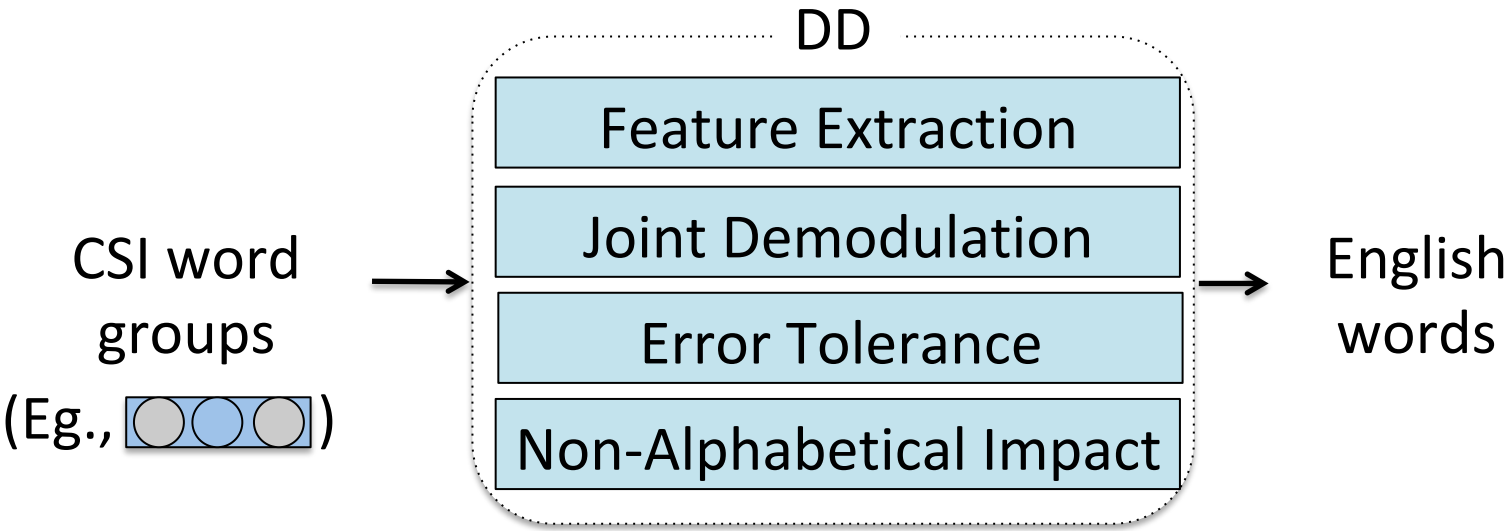
CSI word group

Dictionary demodulation

○ Space-associated

●/●/●/… Non-space-associated

Dictionary Demodulation (DD)



CSI word groups (Eg., ○○○)

DD

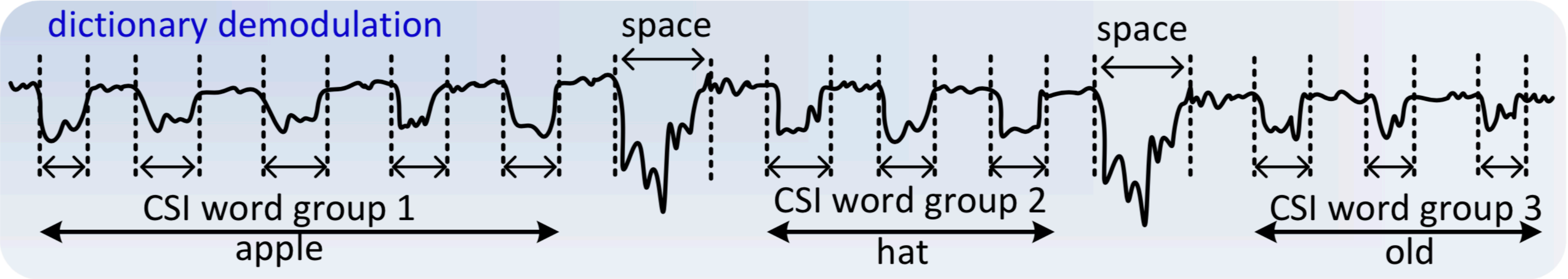
Feature Extraction

Joint Demodulation

Error Tolerance

Non-Alphabetical Impact

English words



Feature Extraction

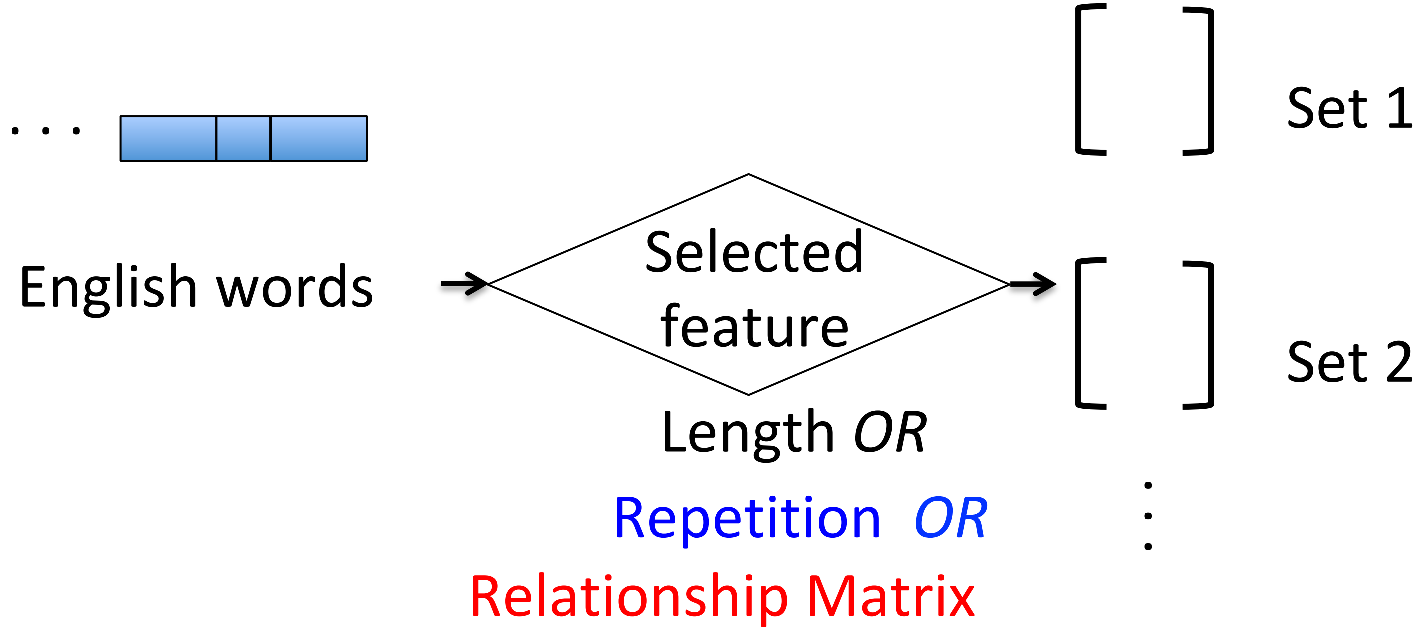
- Length ***L***: number of constituent letters
- Repetition **{*L*, (*t*$_1$, …, *t*$_r$)}**:
  - *r* is the number of distinct letters that repeat,
  - t_i denotes how many times the corresponding letter repeats
- Inter-Element Relationship Matrix ***M***

$$M : [x_1, \ldots, x_n] \mapsto \begin{bmatrix} r_{1,1} & r_{1,2} & r_{1,3} & \cdots & r_{1,n} \\ r_{2,1} & r_{2,2} & r_{2,3} & \cdots & r_{2,n} \\ \cdots & \cdots & \cdots & \cdots & \cdots \\ r_{n,1} & r_{n,2} & r_{n,3} & \cdots & r_{n,n} \end{bmatrix}$$

$r_{i,j} = 1$ if x_i and x_j are same or similar

Feature Extraction

- Dictionary: Top 1,500 most frequently used word list[1]



English words

Selected feature

Length *OR*

Repetition *OR*

Relationship Matrix

Set 1

Set 2

[1] Mark Davies. "Word frequency data from the Corpus of Contemporary American English (COCA)," http://www.wordfrequency.info/free.asp.

Feature Extraction

↑ ***Uniqueness rate*** $= \frac{T_p}{T}$

T_p -- number of sets obtained

T -- number of consider words

Better partitioning (distinguishability)

	Uniqueness rate	Average set cardinality
Length	0.009	107
Repetition	0.042	24
Relationship matrix	0.225	4

Joint Demodulation

- Example:
  - A dictionary **W**={‘among’, ‘apple’, ‘are’, ‘hat’, ‘honey’, ‘hope’, ‘old’, ‘offer’, ‘pen’}.
  - Type in two words: “apple” and “pen”

1) $c_1||\underset{\blacktriangle}{c_2}||\underset{\blacktriangle}{c_3}||c_4||c_5$ ⇨ R_1:

$$\begin{array}{c|ccccc} & c_1 & c_2 & c_3 & c_4 & c_5 \\ \hline c_1 & 1 & 0 & 0 & 0 & 0 \\ c_2 & 0 & 1 & \boxed{1} & 0 & 0 \\ c_3 & 0 & 1 & 1 & 0 & 0 \\ c_4 & 0 & 0 & 0 & 1 & 0 \\ c_5 & 0 & 0 & 0 & 0 & 1 \end{array}$$

2) compute the relationship matrix for each word in **W**, and compare each with R_1 ⇨ Candidates: “apple” and “offer”

Joint Demodulation

3) $\boxed{c_6||c_7||c_8}$ ⇨ Candidates: {“hat”, “old”, “are”, “pen”}

4) $c_1||c_2||c_3||c_4||c_5||c_6||c_7||c_8$ ⇨ R_{new}

5) Candidates **T** of the two-word sequence,

{“apple||hat”, “apple||old”, “apple||are”, “apple||pen”, “offer||hat”, “offer||old”, “offer||are”, “offer||pen”}

6) Generate the relationship matrix for each new candidate in **T** and compare it with R_{new}

⇩

Final result: “apple||pen”

Joint Demodulation

- Input:
  - *m* CSI word groups **S** = {S_1, S_2, …, S_m};
  - dictionary with *q* words **W** = {W_1, W_2, …, W_q}
- Output:
  - a corresponding phrase of *m* words
- Observation:
  - each CSI word group => multiple candidate words
  - each candidate => <CSI sample, letter> mapping info

Joint Demodulation

Step 1: find initial candidate words for each CSI word group

$R_{\text{CSI word group}} \leftarrow$ Compare $\rightarrow R_{\text{each word}}$

=> match, add the word as a candidate;
no match, add the CSI word group to the "undemodulated set" **U**

Joint Demodulation

Step 2 (iteratively):

(a) T_i : concatenation of the first i-1 demodulated CSI word groups; candidates for T_i are $\{T_{i1}, T_{i2}, \ldots, T_{ip}\}$

(b) S_i : the i-th CSI word group;

candidates for S_i are $\{S_{i1}, S_{i2}, \ldots, S_{iq}\}$ (by step 1)

(c) Find new candidates for concatenated CSI word groups

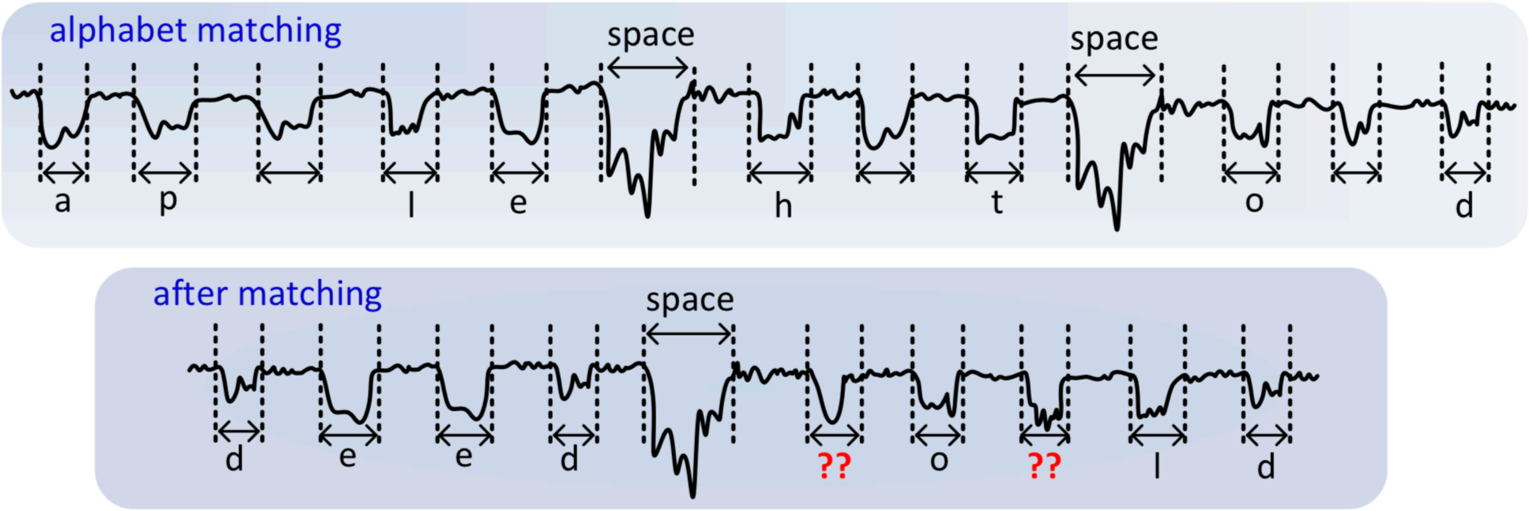
$R_{T_i||S_l} \longleftarrow$ Compare $\longrightarrow R_{T_{ij}||S_{ik}}$ $(1<=j<=p, 1<=k<=q)$

=> match, add $T_{ij}||S_{ik}$ as a candidate for T_{i+1} ;

no match, add S_i to **U** and **skip** to S_{i+1}

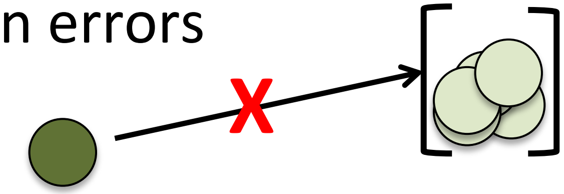
Joint Demodulation

- Alphabet matching: the mapping can be applied to the remaining CSI word groups and those in **U**
  - Example: the user types “deed” || “would” after the mapping is established;



Error/Non-Alphabetical Characters Tolerance

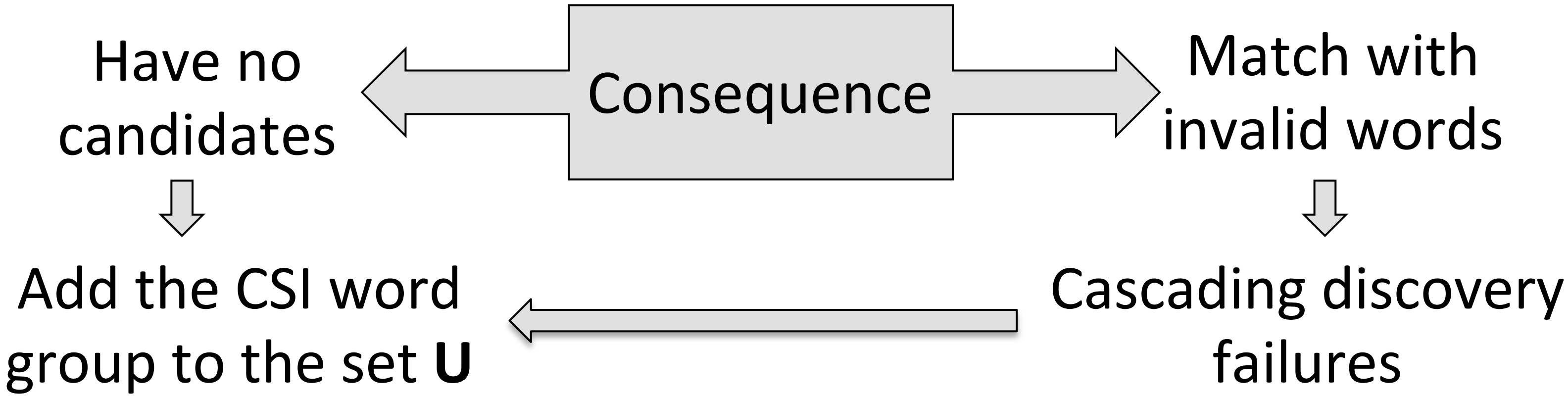
- Abnormal situations:
  - CSI classification errors



A CSI sample for the letter

Set of CSI samples for the letter

  - Typos/Non-Alphabetical Characters



Consequence

Have no candidates

Match with invalid words

Add the CSI word group to the set **U**

Cascading discovery failures

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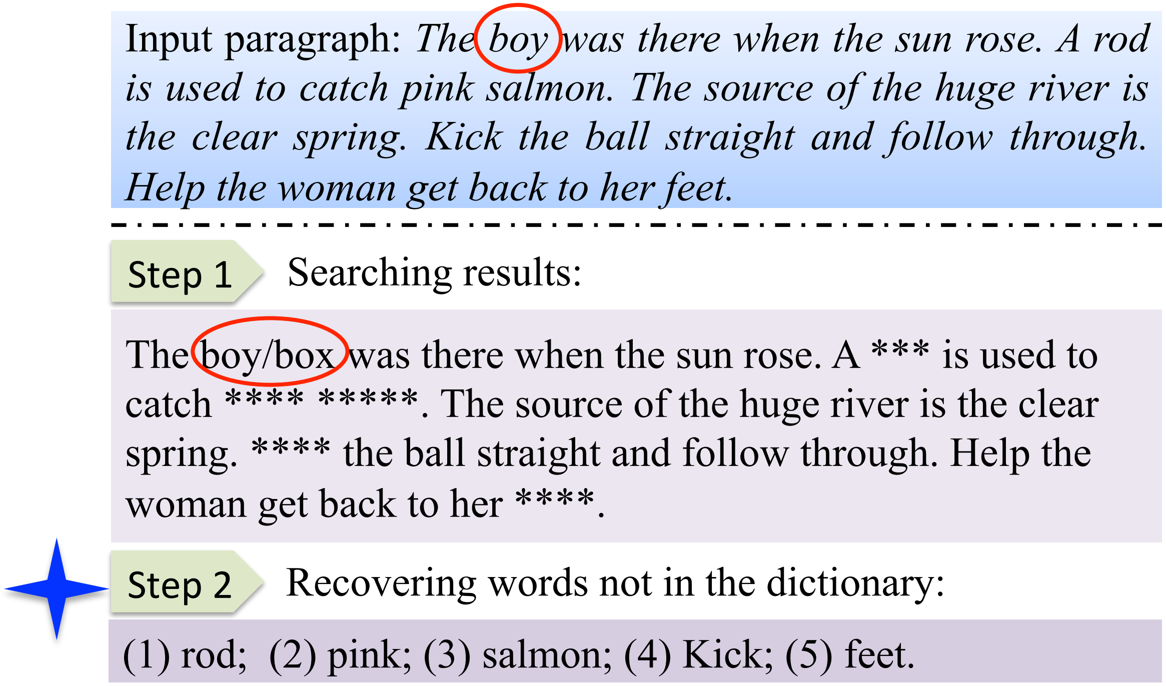
Experiment Results

- Attack system:
  - a wireless transmitter + a receiver (each is a USRP connected with a PC)
  - the channel estimation algorithm runs at the receiver to extract the CSI for key inference.
  - dictionary: Top 1,500 most frequently used word list

- Target user:
  - a desktop computer with a Dell SK-8115 USB wired standard keyboard

Example Recovery Process

- Randomly select 5 sentences from the representative English sentences in the Harvard sentences[2].



Input paragraph: *The boy was there when the sun rose. A rod is used to catch pink salmon. The source of the huge river is the clear spring. Kick the ball straight and follow through. Help the woman get back to her feet.*

Step 1 Searching results:

The boy/box was there when the sun rose. A *** is used to catch **** *****. The source of the huge river is the clear spring. **** the ball straight and follow through. Help the woman get back to her ****.

Step 2 Recovering words not in the dictionary:

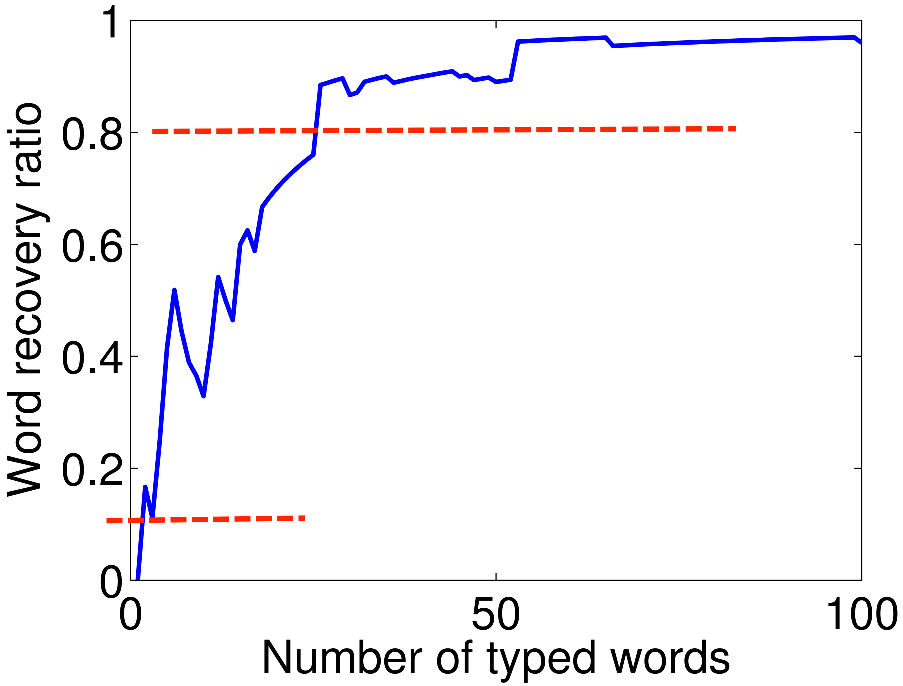
(1) rod; (2) pink; (3) salmon; (4) Kick; (5) feet.

[2] IEEE Subcommittee on Subjective Measurements. “IEEE Recommended Practice for Speech Quality Measurements,” *IEEE Transactions on Audio and Electroacoustics*, vol. 17, no. 3 (Sep 1969), pp. 227–246.

Eavesdropping Accuracy

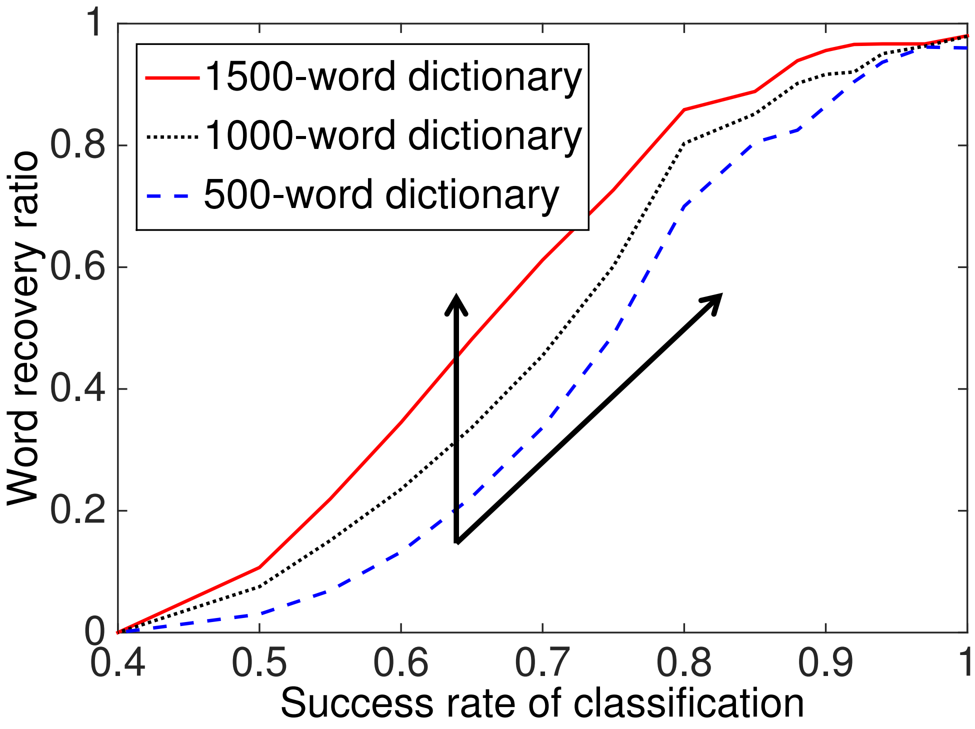
$$\text{Word recover ratio} = \frac{\text{\# of successfully recovered words}}{\text{total \# of input words}}$$

- Single article recovery (Type a piece of CNN news)



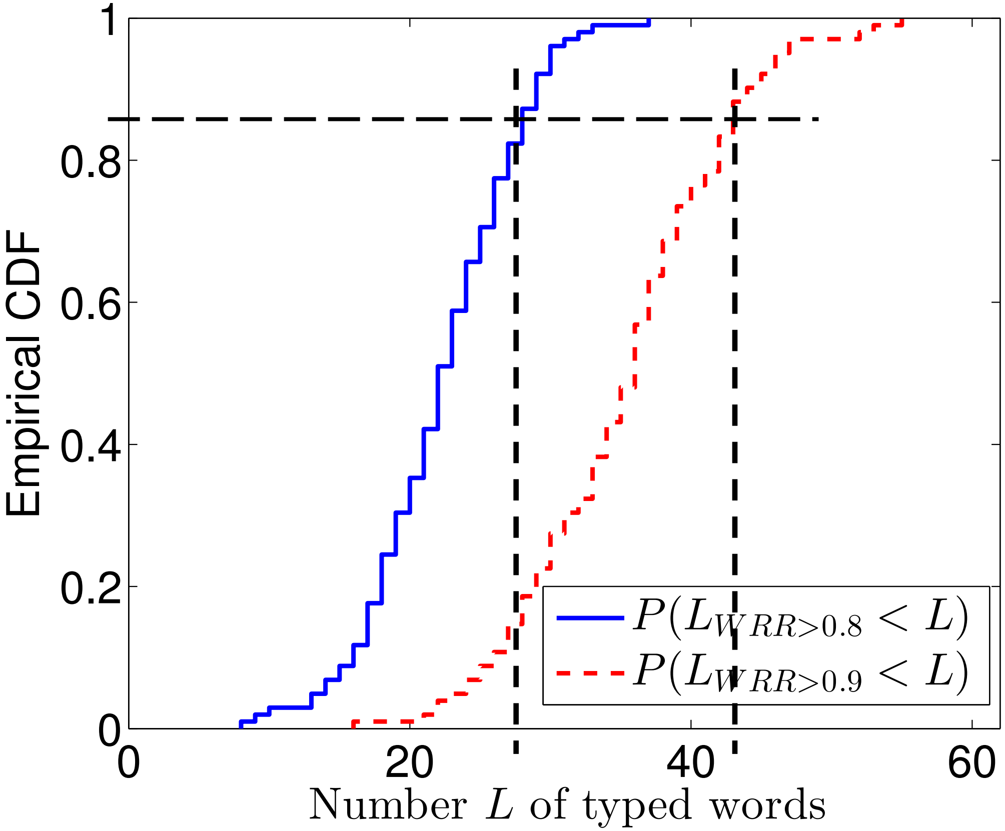
Impact of CSI Sample Classification Errors

- We artificially introduce errors into the groupings.



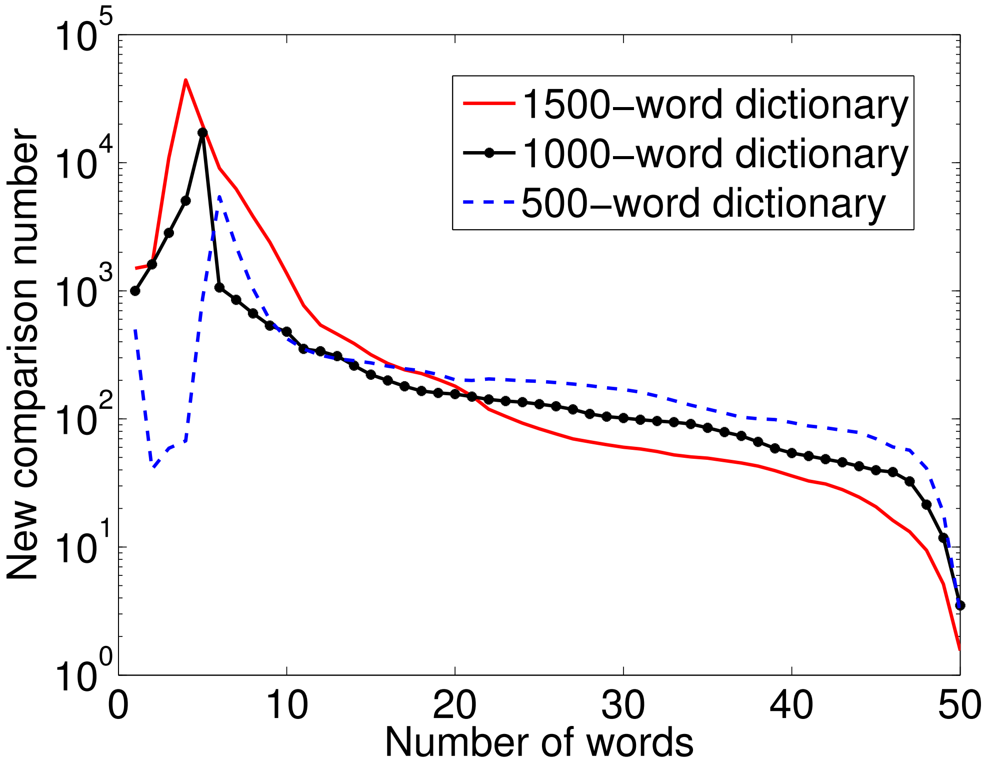
Overall Recovery Accuracy

- $L_{WRR>x}$ denotes the required number of typed words from each article to satisfy the ratio *x*.



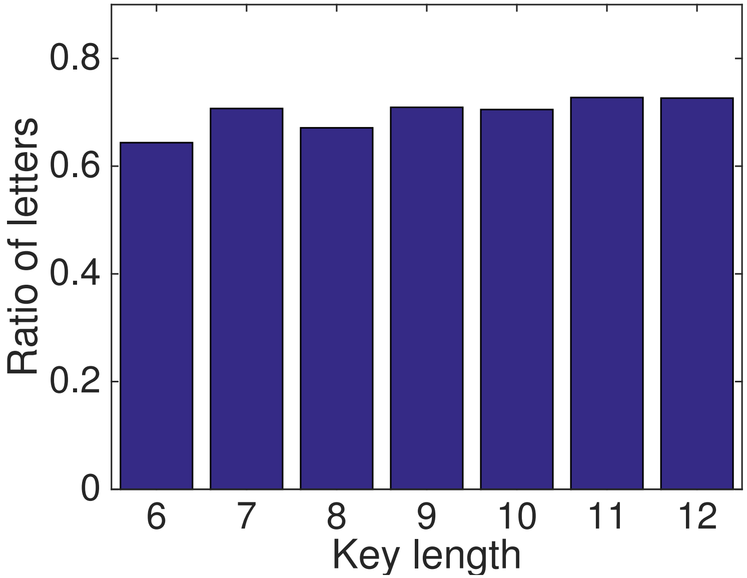
Time Complexity Analysis

- The comparison of relationship matrices is the dominant part of the demodulation phase.



Password Entropy Reduction

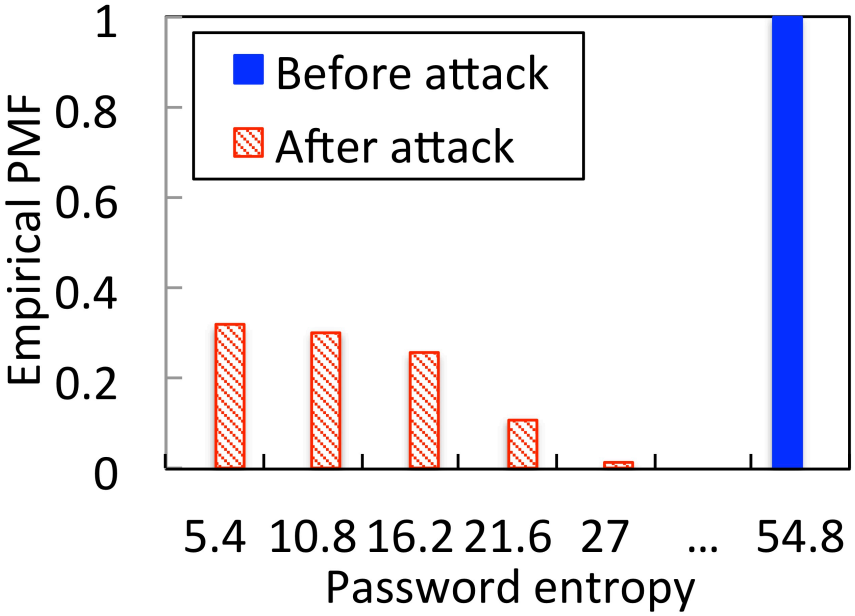
- The higher the entropy, the more the randomness
- 2012 Yahoo! Voices hack[3]: 342,508 passwords: 98.42% of passwords are 12 characters or fewer



[3] 2012 Yahoo! Voices hack. https://en.wikipedia.org/wiki/2012_Yahoo!_Voices_hack

Password Entropy Reduction (Cont'd)

- Breaking a 9-character password is reduced to guessing 1-5 non-letter characters.



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Conclusion

- ✓ Identify a new type of keystroke eavesdropping attack bypassing the training requirement

- ✓ Create a joint demodulation algorithm to establish the mapping between a letter and a CSI sample

- ✓ Implement this attack on software-defined radio platforms and conduct a suite of experiments to validate its impact

Thank you!
Any questions?