Wireless Network Security and Privacy
Autumn 2023

Xiaoyu Ji

Physical Layer Threats; Jamming

PHY

Wireless PHY

- The wireless PHY is responsible for delivering a bit stream from a transmitter to one or more receivers. It's not as easy as it sounds.
- Tx/Rxs need to be coordinated in time, space, frequency, phase, encoding/language
- Wireless means there are many sources of error, reasons for failure, etc.

PHY Standards

- In WiFi networks, IEEE 802.11 defines several versions of the PHY, including extensions for mesh, vehicular, etc.

- In telecom, the GSM 05.xx series defines the Um physical layer, and other standards build on it, including ITU-T standards like 4G.

- In PANs, standards like 802.15.1 (Bluetooth), .3 (high-rate, e.g., UWB), and .4 (low-rate, e.g., Zigbee) all define their own PHY models.

Wireless PHY Services

- Various parts of PHY operation:
  - **Radio interface**: spectrum allocation, signal strength, bandwidth, carrier sensing, phase sync, …
  - **Signal processing**: equalization, filtering, training, pulse shaping, signaling, …
  - **Coding**: channel coding, bit interleaving, fwd error correction, …
  - **Modulation** (mapping bits to signals)
  - Topology,antennas, duplex/simplex, multiplexing, and so much more
- PHY is typically the most complex part of a wireless network

What are the basic threats faced at the PHY layer?

Back to the Party

Physical Layer Misbehavior

- Open, shared medium is vulnerable
  - Anyone can "talk" → greedy or malicious nodes can easily interfere
    - Prevention/degradation of communication via jamming
    - Cutting off available resources influences network control, operation, and performance
  - Anyone can "listen" → curious or malicious nodes can easily eavesdrop on communication
    - Recovery of information exchanged by neighbors (violation of data, identity, operation/intention privacy)
    - Inference/learning, tracking, observing

Challenges

- How can we prevent a curious or malicious party from eavesdropping on wireless transmissions at the physical layer?

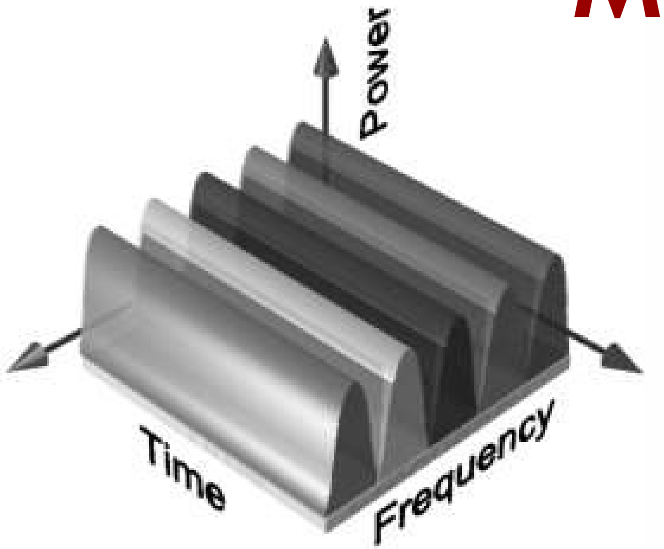
- How can we prevent a greedy or malicious party from interfering with PHY transmission and reception?

- For both:
  - Short answer, we can't
  - However, we can make it much more difficult

Spread Spectrum

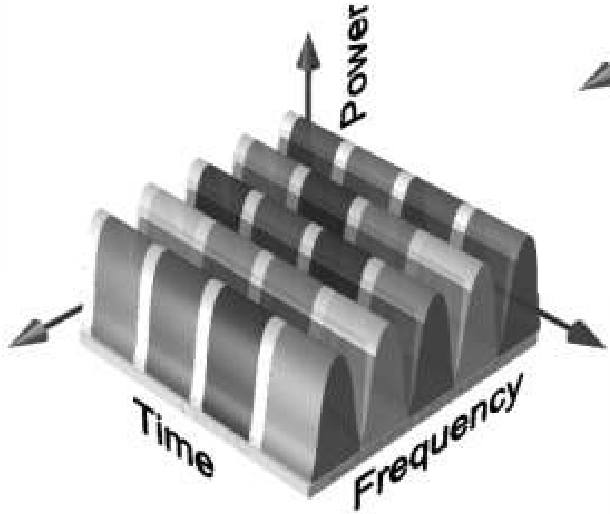
- Spread spectrum is an extension of multiplexing that uses randomization to increase diversity and improve performance in various ways
  - Frequency-hopping spread spectrum (FHSS) builds on FDM allowing devices to pseudo-randomly move among frequency channels
    - If one channel is particular good or bad, everyone shares it randomly
  - Direct-sequence spread spectrum (DSSS) builds on CDM allowing devices to pseudo-randomly move among different code spaces
    - Code spaces are analogous to frequency bands

Multiplexing

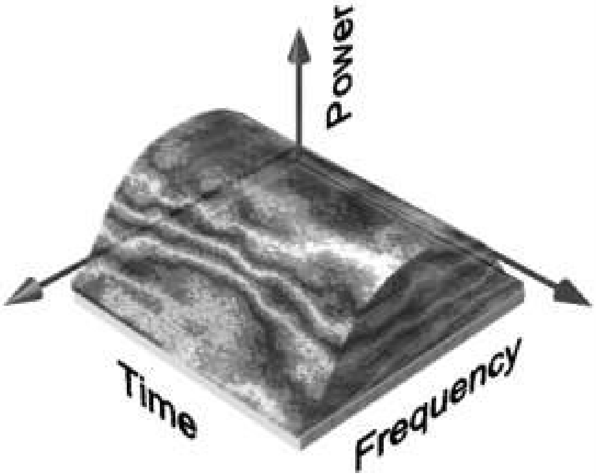


FDM – frequency division multiplexing

TDM – time division multiplexing (flip x-y)



TDM + FDM as in GSM

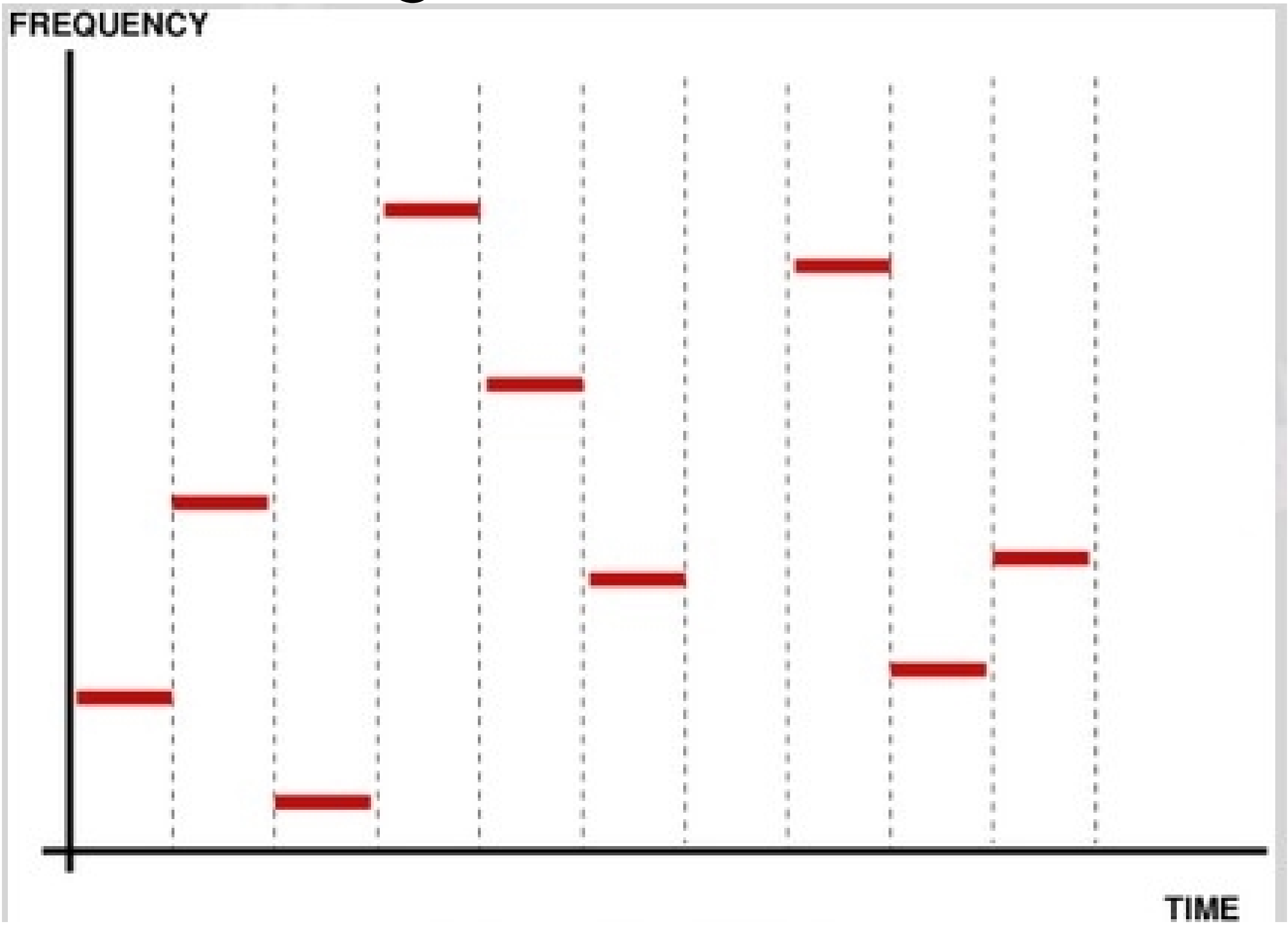


CDM – code division multiplexing

images from [Erik Lawrey; SkyDSP.com]

FHSS

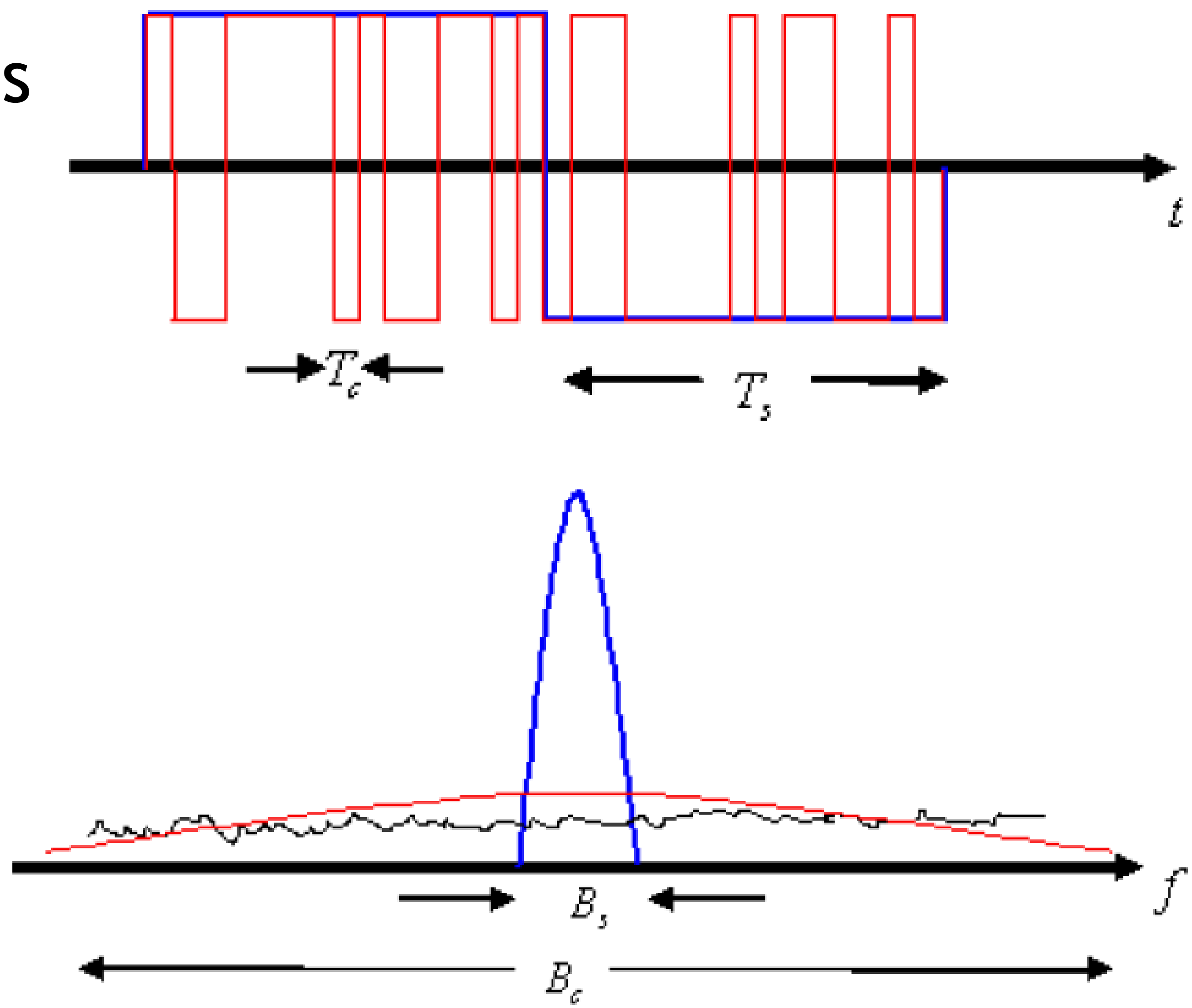
- FHSS: Sender and receiver synchronize a hopping pattern over a large bandwidth



DSSS Encoding

- DSSS encoding maps long symbols to sequences of short chips

- Shorter chip duration means wider bandwidth



Benefits

- FHSS:
  - Narrow-band interference only has an effect for a small fraction of the time
  - Single-channel eavesdroppers can't “follow” the signal, need to use much wider bandwidth to hear everything
- DSSS:
  - Narrow-band interference is “despread” at the receiver, more like quiet wide-band noise
  - Other signals are (nearly) orthogonal
  - Eavesdropper has to know/guess code to decode

Cryptographic SS

- Building off basic spread spectrum, we can add cryptographic randomization to make hopping schedule and code sequences secret
  - Using a symmetric key as a seed to a pseudo random number generator (PRNG) makes the hopping schedule or code sequence secret

- In both cases, this requires symmetric key management, which has its own issues

Issues with Spread Spectrum

- To be effective against curiosity/greed/malice, hopping sequences (FHSS) and spreading codes (DSSS) must be **private**
  - In many implementations, these codes are given to all group members – if becoming a group member is easy, there's no barrier
  - If group membership is tightly guarded, can it be bought or stolen?
- If codes can't be obtained, can they be learned?
  - Code reuse allows for statistical analysis and recovery

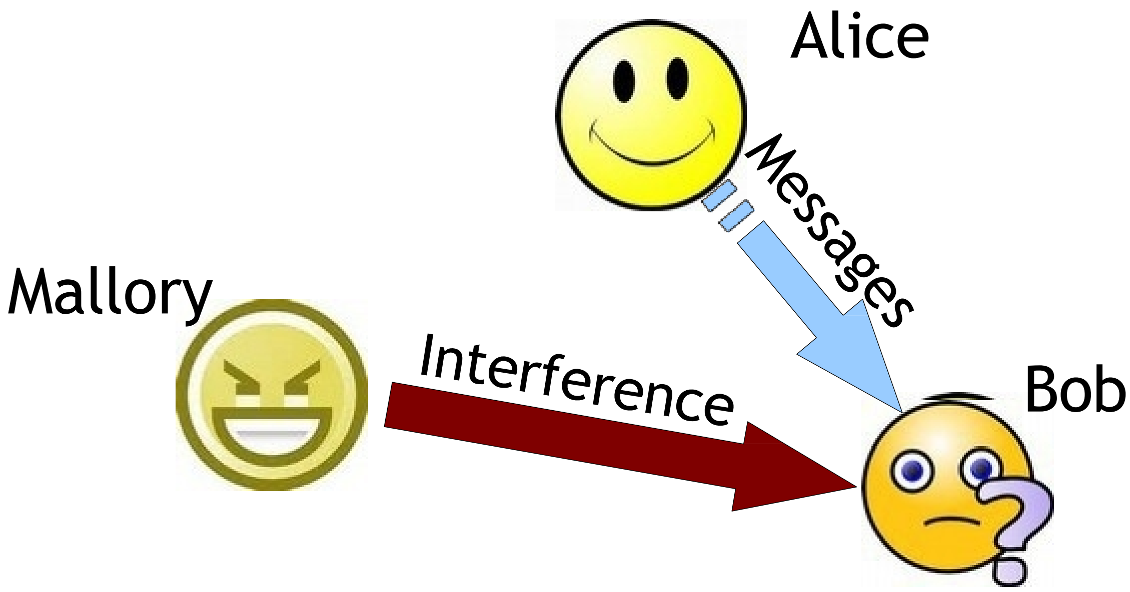
Further Hardening the PHY

- If spread spectrum isn't enough, what else?
  - Multiple diversity can protect against multiple threats at numerous levels
  - Implementations must consider the threat models and adapt to unexpected behaviors
    - Prevent statistical analysis, adapt to learning adversaries

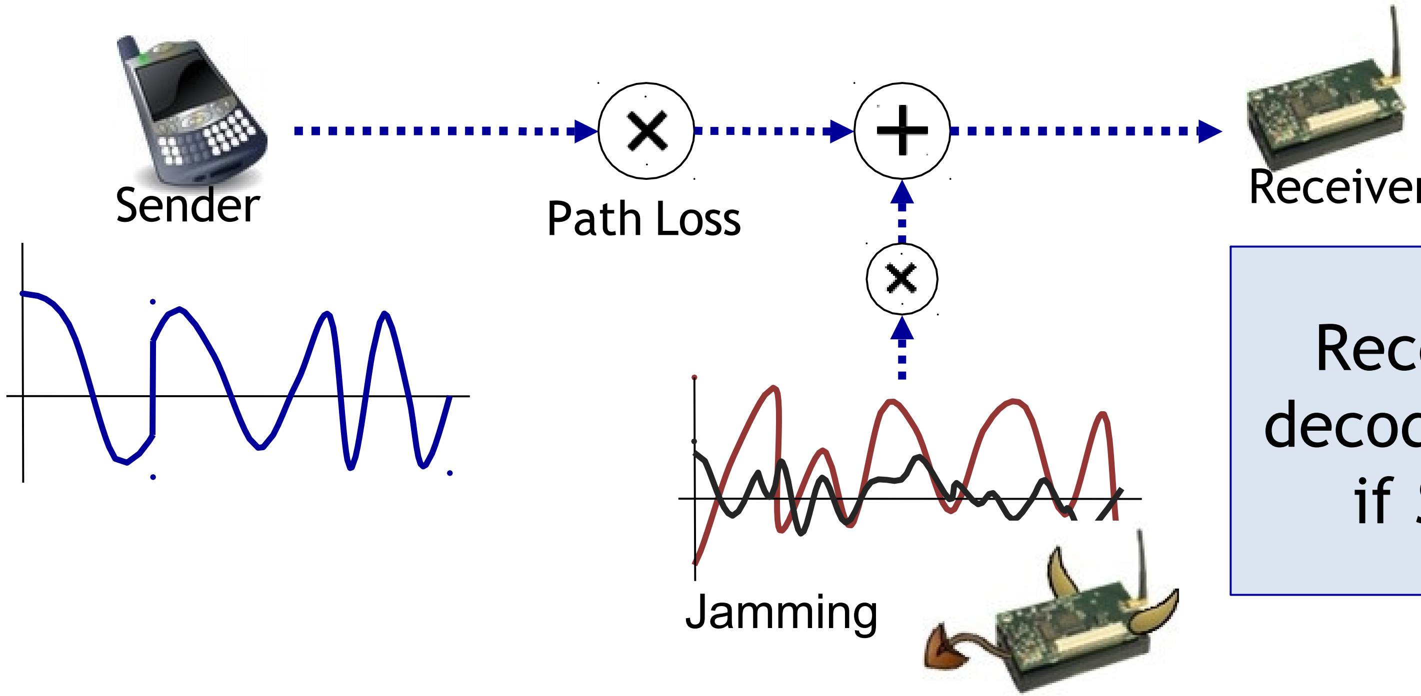
Let's focus on Jamming

Jamming

- Conceptually, jamming is a physical layer denial-of-service attack that aims to prevent wireless communication between parties



How Does Jamming Work?

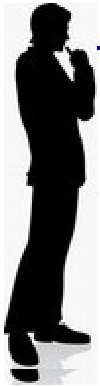


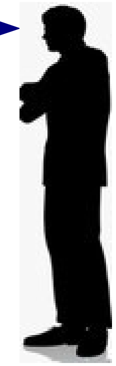
Receiver can decode message if *SINR* $\geq \tau$

Jamming decreases *SINR*, causes ***decoding failure*** and ***packet loss***

But, it's much more complicated than that...

Geometry Matters





Attacker can be MUCH
quitter than the speaker

SINR metric captures effects of geometry

SINR = (Rx signal power) / (noise power + Rx jamming power)

Often modeled as $P_{tr} = k_t P_t d_{tr}^{-a}$

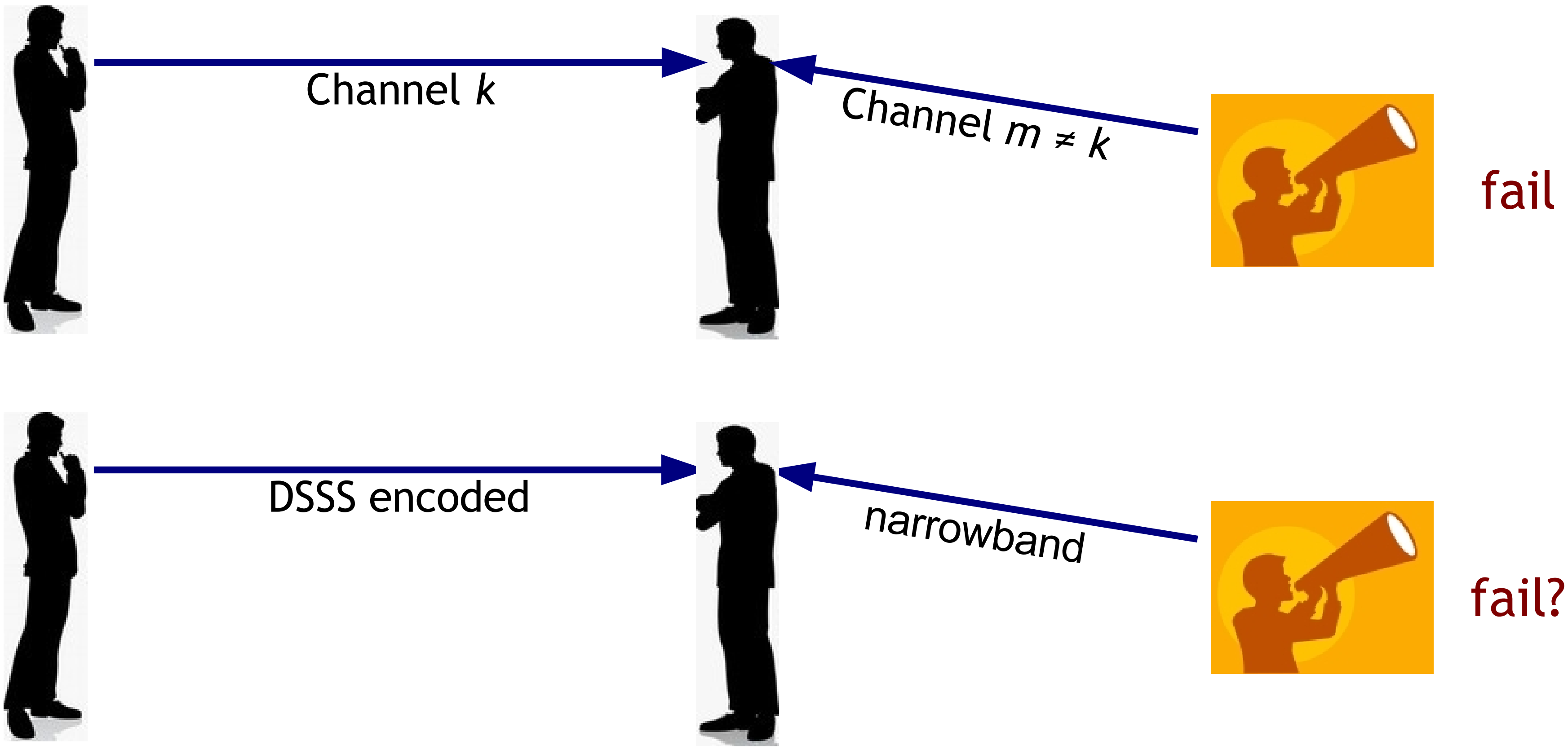
Typically random variable N_0

Often modeled as $P_{jr} = k_j P_j d_{jr}^{-a}$

Timing Matters

Can be modeled as a (random) multiplier in the "I" term of the SINR metric

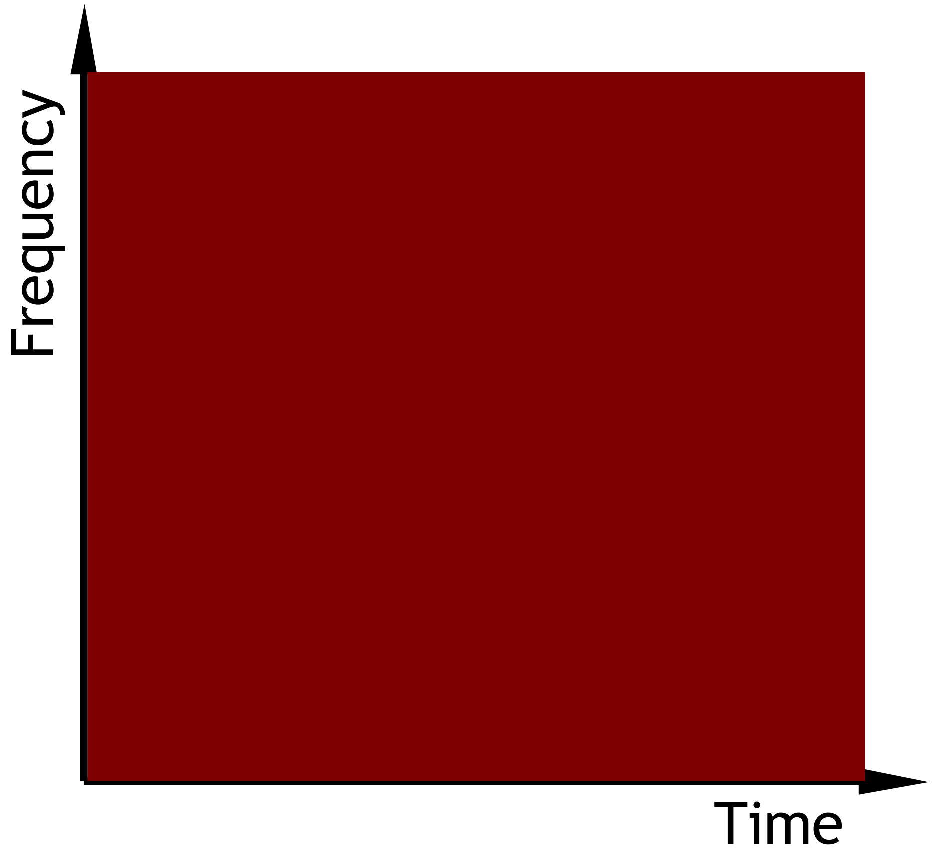
Orthogonality Matters



Generalized Jamming

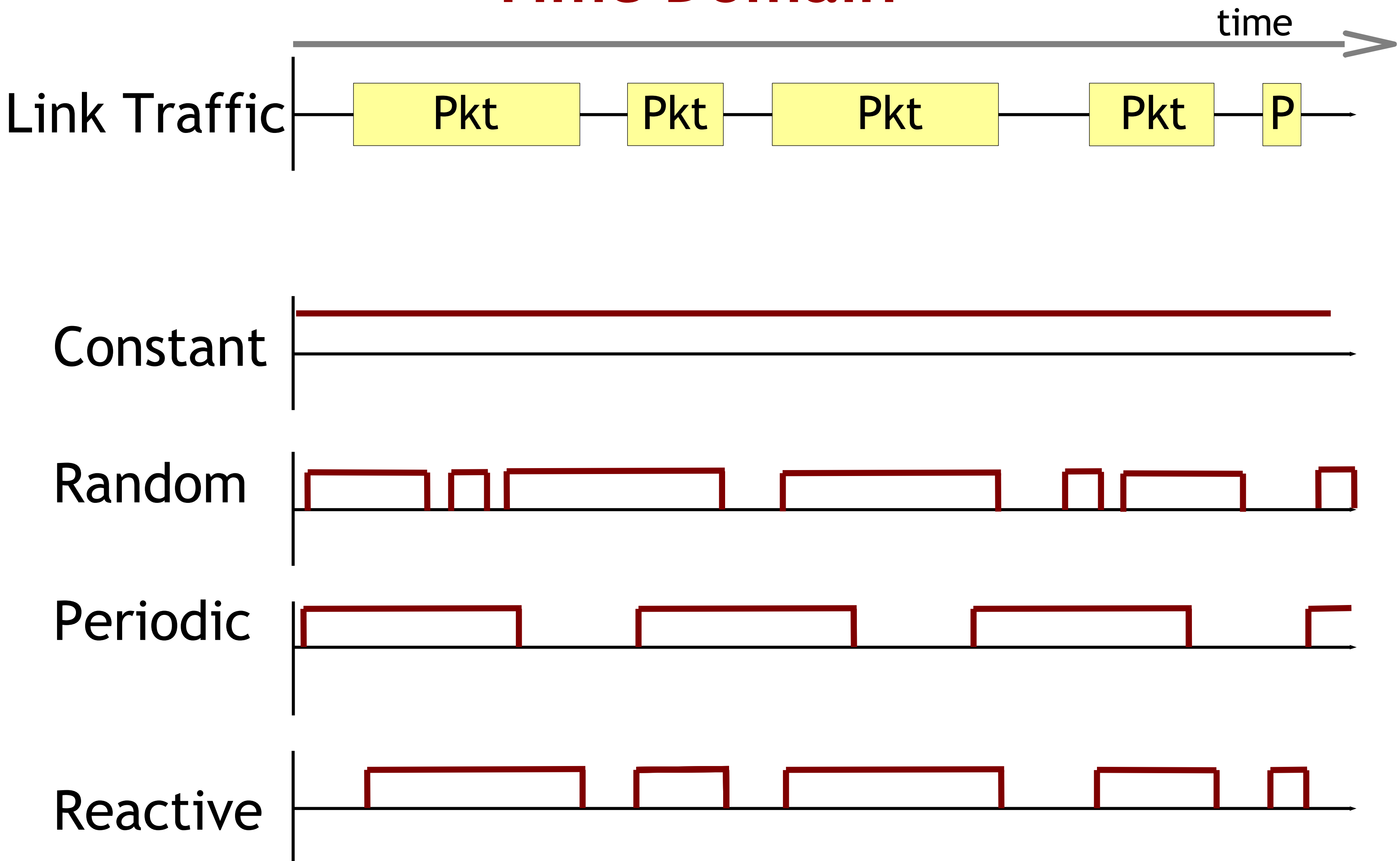
- A jammer allocates energy/signal to diverse time, freq, etc. resources according to an attack strategy *S*
  - Effect *E*(*S*) of the attack
  - Cost *C*(*S*) of the attack
  - Risk *R*(*S*) of being detected / punished

  - With other metrics, an optimization emerges



Jamming Strategies

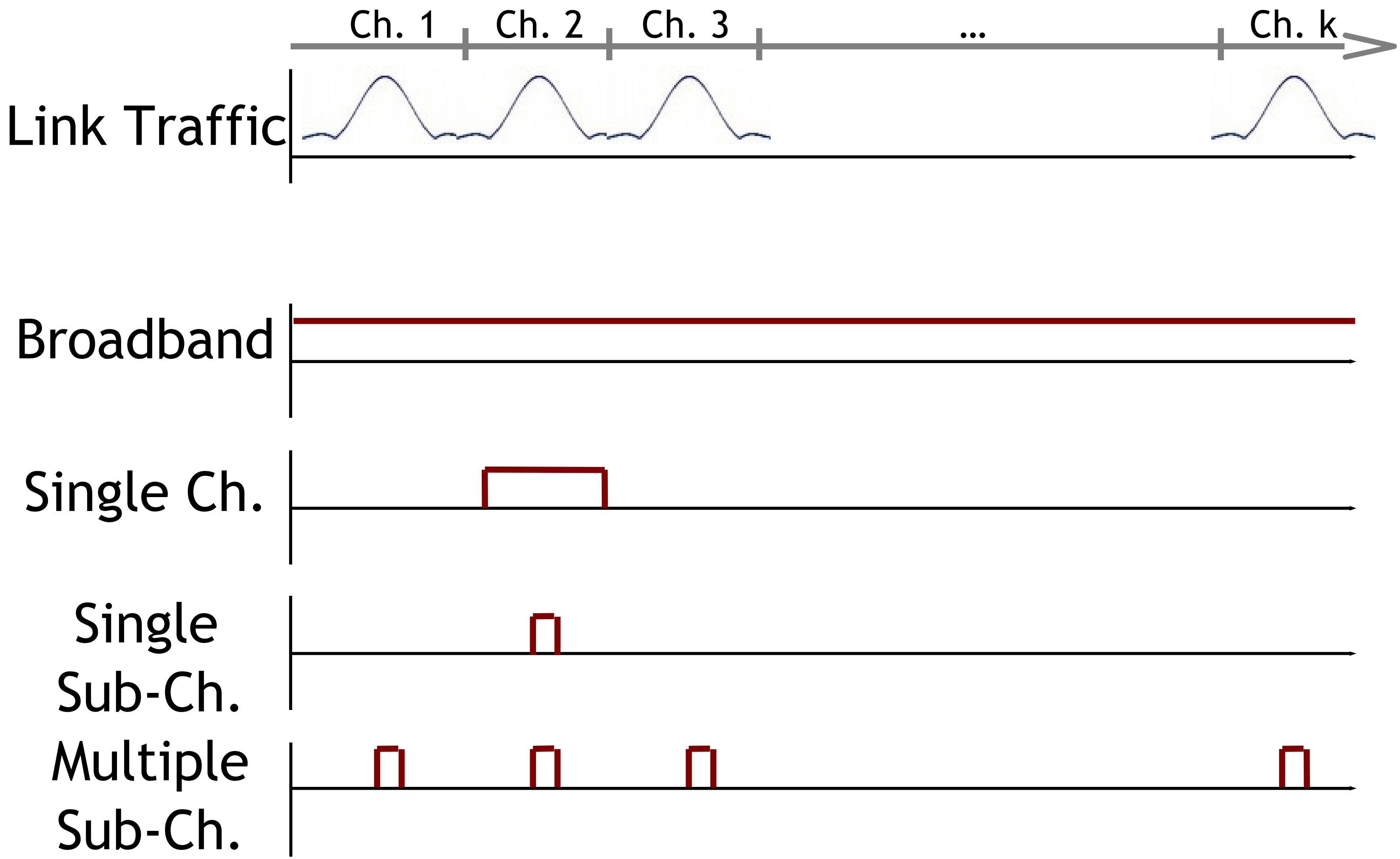
Time Domain



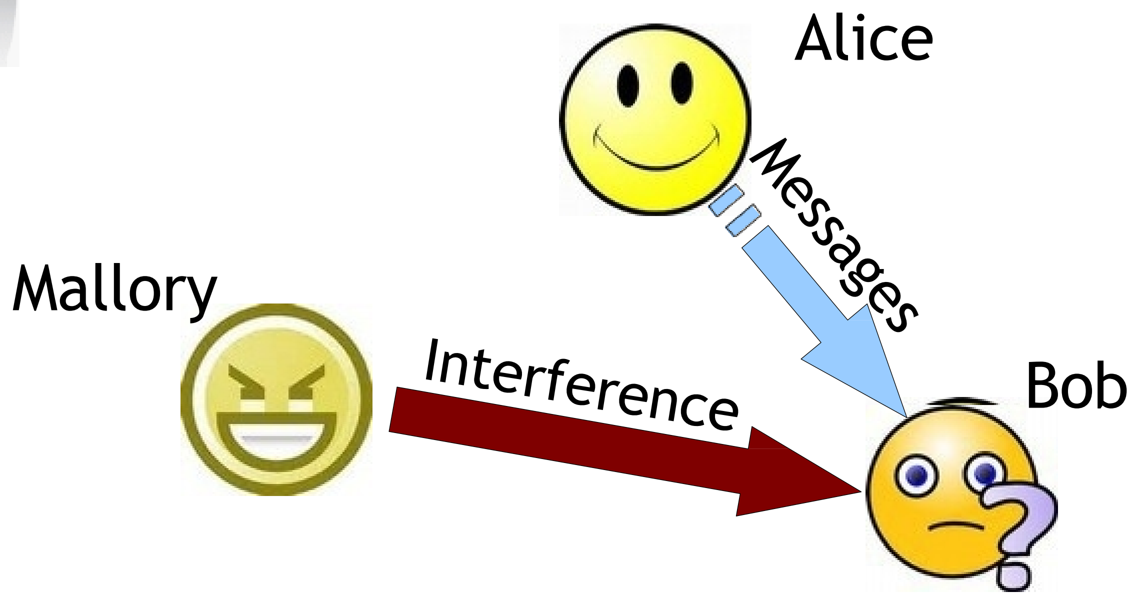
[Xu et al., 2006; Mpitziopoulos et al., 2009]

Jamming Strategies

Frequency Domain



Jamming



How can we protect against jamming?

Jamming Detection & Defense

[Xu et al., IEEE Network 2006]

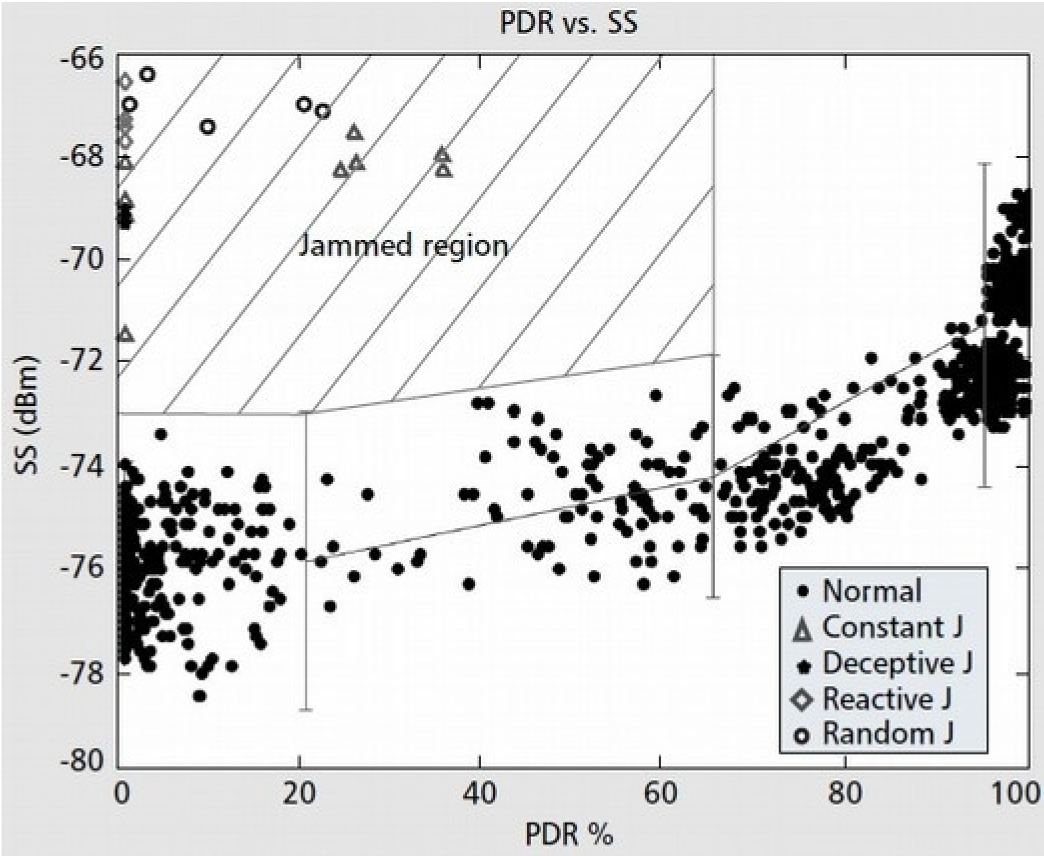
- **Goal**: detect and localize jamming attacks, then evade them or otherwise respond to them
- **Challenge**: distinguish between adversarial and natural behaviors (poor connectivity, battery depletion, congestion, node failure, etc.)
  - Certain level of detection error is going to occur
  - Appropriate for deployment in wireless networks
- **Approach**: coarse detection based on packet observation

Basic Detection Statistics

- Received signal strength (RSSI)
  - Jamming signal will affect RSSI measurements
  - Very difficult to distinguish between jamming/natural
- Carrier sensing time
  - Helps to detect jamming as MAC misbehavior
  - Doesn't help for random or reactive cases
- Packet delivery ratio (PDR)
  - Jamming significantly reduces PDR (to ~0)
  - Robust to congestion, but other dynamics (node failure, outside comm range) also cause PDR $\rightarrow 0$

Advanced Detection

- Combining multiple statistics in detection can help
  - High PDR + High RSSI → OK
  - Low PDR + Low RSSI → Poor connectivity
  - Low PDR + High RSSI → ? → Jamming attack?

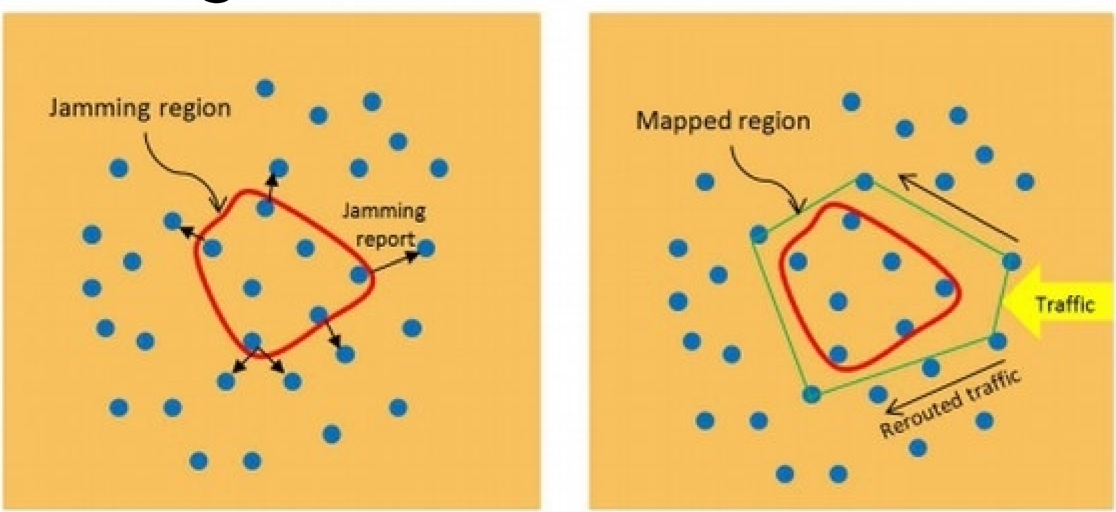


Caveat: this assumes RSSI can be accurately measured

See [DeBruhl & Tague, SECON 2013]

Jammed Area Mapping

- Based on advanced detection technique, nodes can figure out when they are jammed
- At the boundary of the jammed area, nodes can get messages out to free nodes
- Free nodes can collaborate to perform boundary detection using location information



Evading Jamming

- Nodes in the jammed region can evade the attack, either spectrally or spatially
  - Spectral evasion → "channel surfing" to find open spectrum and talk with free nodes
  - Spatial evasion → mobile retreat out of jammed area
    - Need to compensate for mobile jammers ability to partition the network (see figure in paper)

What about dynamic attack and defense strategies?

Optimal Jamming & Detection

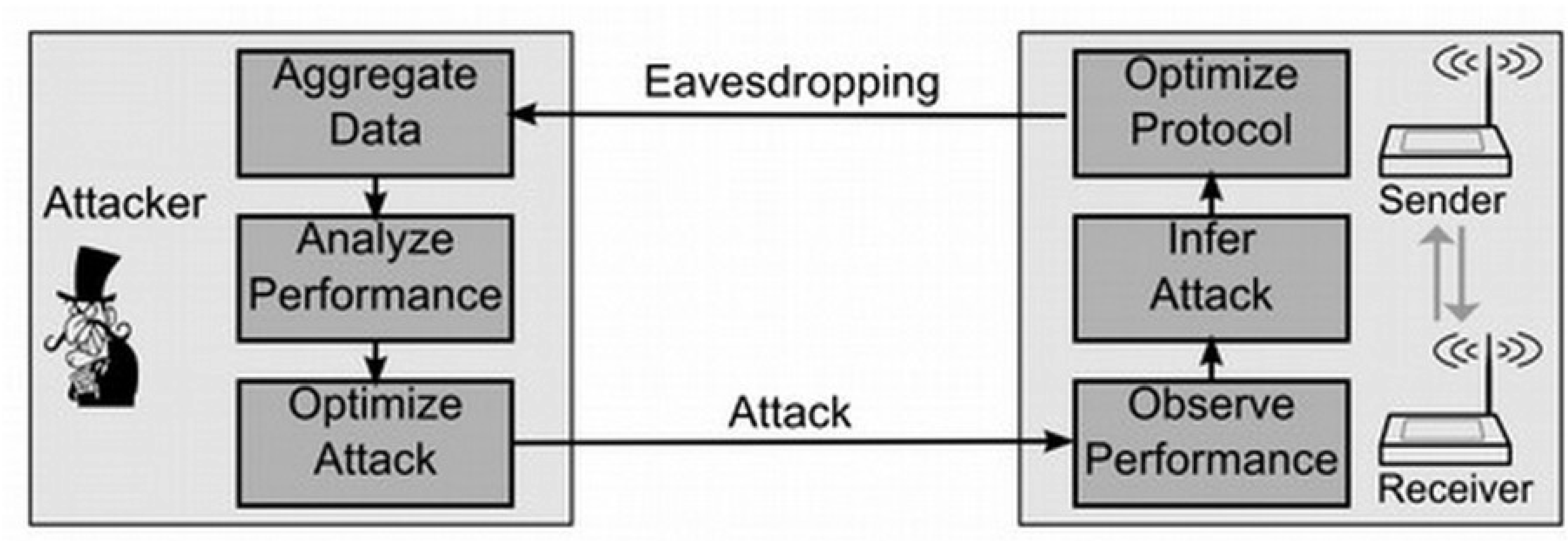
[Li et al., Infocom 2007]

- **Problem setup:** each of the network and the jammer have control over random jamming and transmission probabilities
  - Network parameter γ is probability each node will transmit in a time slot
  - Attack parameter β is probability the jammer will transmit in a time slot
- Opponents can learn about goals through observation and optimize for min-max/max-min

Jamming Games

[DeBruhl & Tague, PMC 2014]

- What if both the attacker and defender are freely adapting in response to each other?

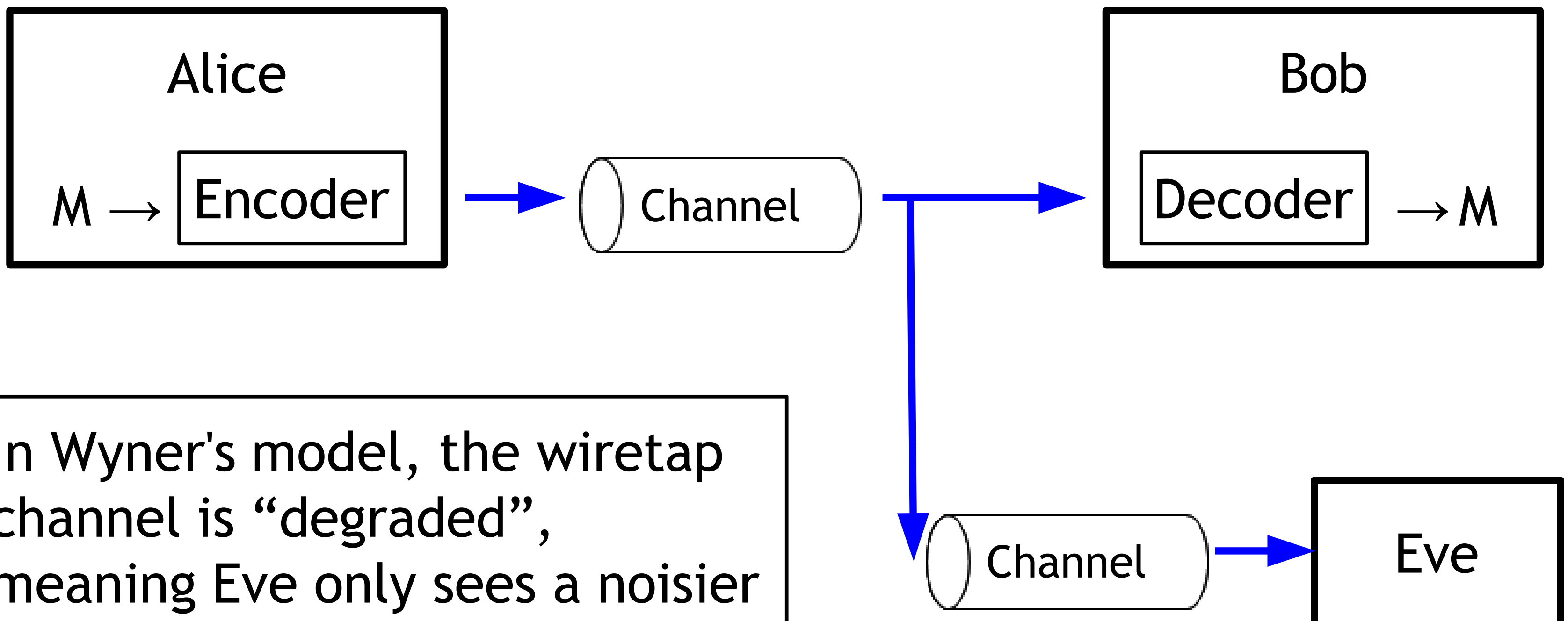


Eavesdropping / Snooping

How can the properties of the wireless medium actually **help** to achieve secure communication?

“Wiretapping”

- In 1975, A. D. Wyner defined the wiretap channel to formalize eavesdropping



In Wyner's model, the wiretap channel is “degraded”, meaning Eve only sees a noisier signal than Bob sees

Secrecy Capacity

- Since the Alice $\rightarrow$ Eve channel is noisier than the Alice $\rightarrow$ Bob channel:
  - Eve can't decode everything that Bob can decode
  - i.e., there exists an encoding such that Alice can encode messages that Bob can decode but Eve can't
  - There's a really nice Information Theory formalization of the concept of secrecy capacity, namely the amount of secret information Alice can send to Bob without Eve being able to decode
  - I'll leave the details for you to explore

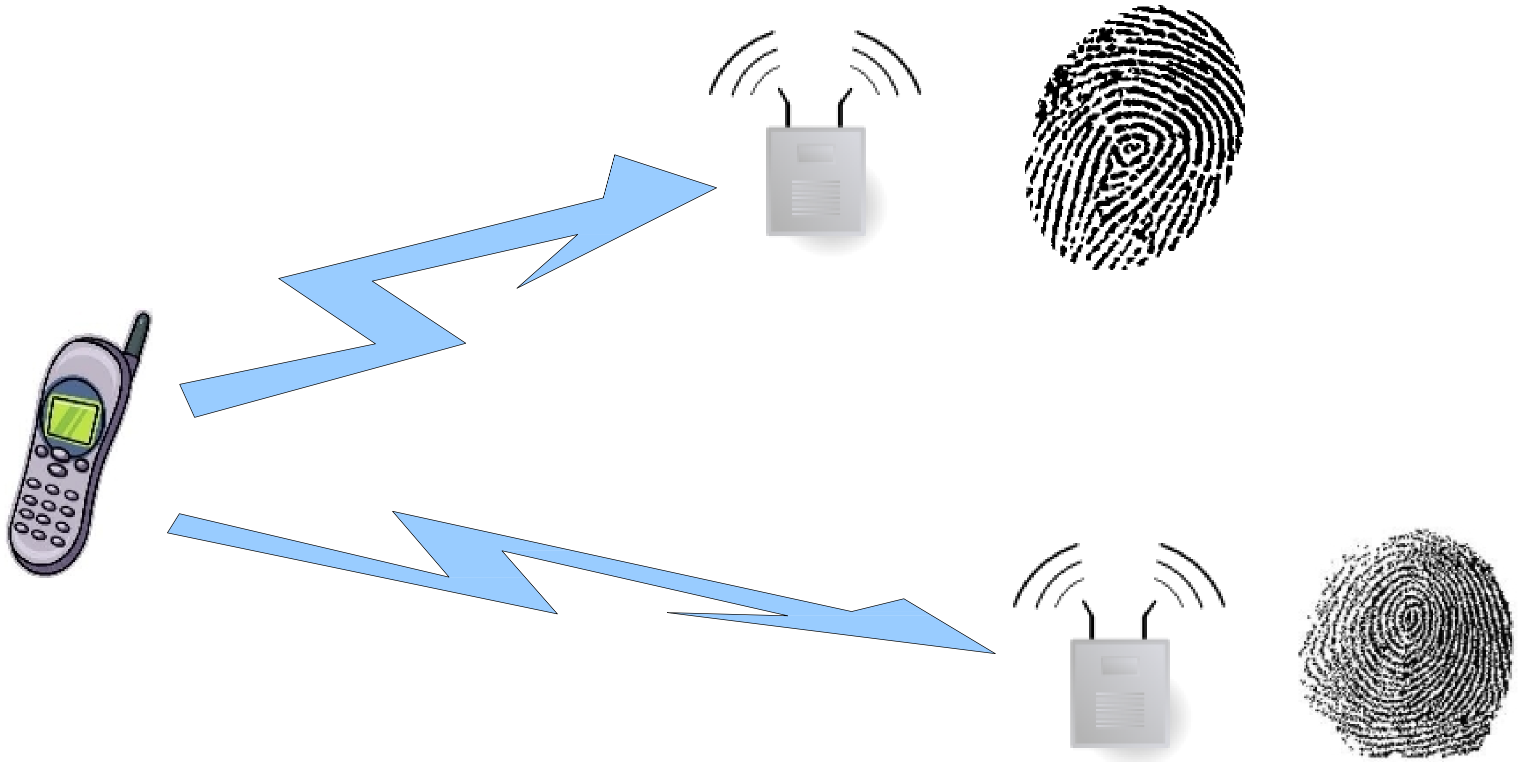
Degraded Eavesdropper?

- In a practical scenario, is it reasonable to assume the eavesdropper's signal is more degraded than the receiver's?
  - Probably not.

- What else can we do to tip the scales in the favor of the Alice-Bob channel?

Diversity of Receivers

The signal emitted by a transmitter looks "different" to receivers in distinct locations



Measurement + Feedback

- Channel State Information (CSI):
  - CSI is the term used to describe measurements of the channel condition
  - If Alice knows the CSI to Bob and to Eve, she can find an appropriate encoding using the measurements
  - If Alice and Bob interact repeatedly, the measurement and feedback actually **increase the secrecy capacity**
    - This can allow for secrecy capacity >0 *even if Eve's channel is less noisy than Bob's channel*

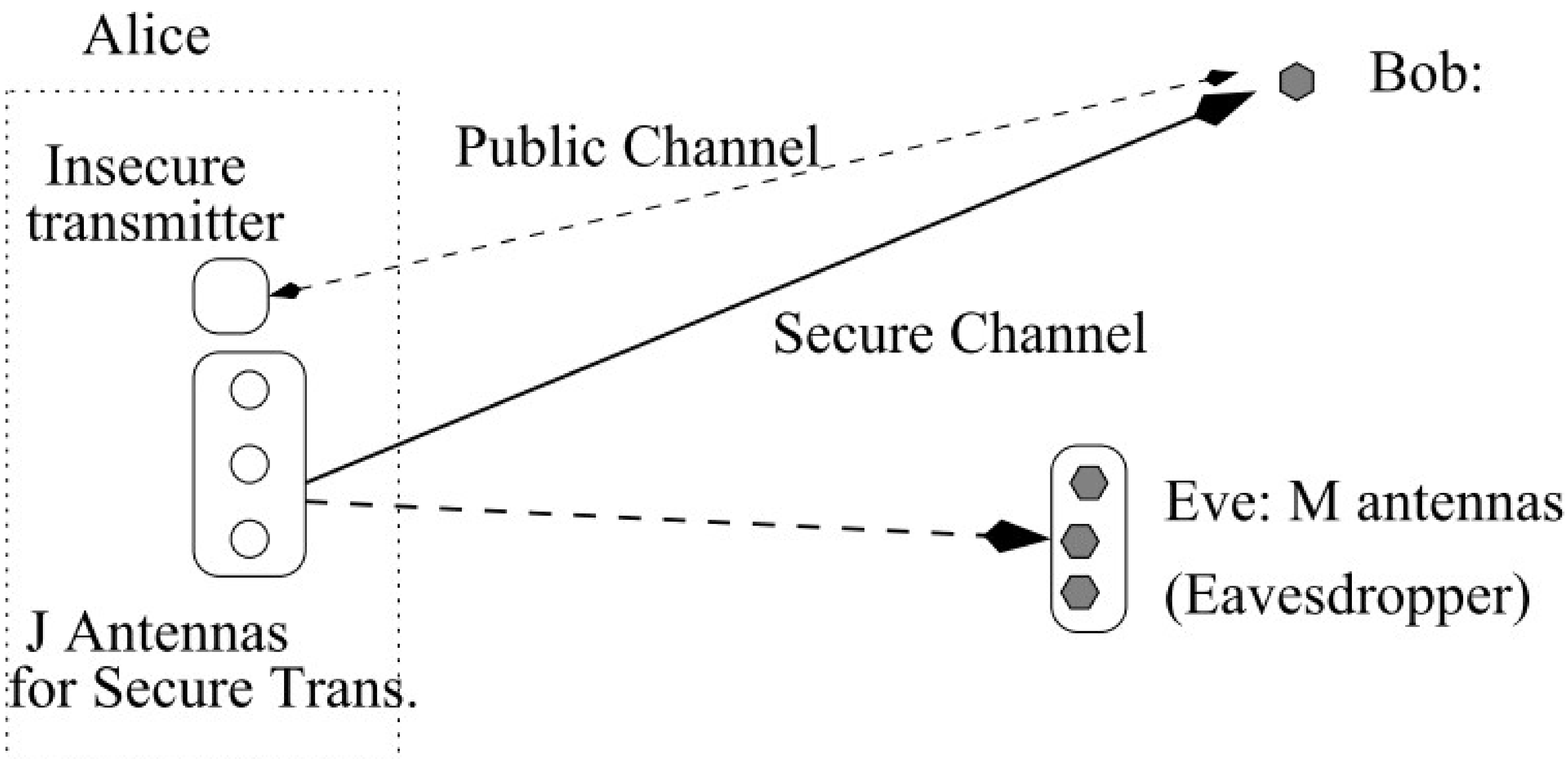
Jamming for Good

- If Alice has diversity in the form of multiple radios or some collaborators:
  - Alice & friends can use a jamming attack to prevent Eve from eavesdropping
  - As long as they don't jam Bob at the same time
  - **Ex:** if the deployment geometry is known, Alice can adjust power, antenna config, etc. so Bob's SINR is high but Eve's is low

Secure Array Transmission

[Li, Hwu, & Ratazzi, ICASSP 2006]

- Antenna control can be used for transmission with *low probability of interception*



Application

- Building on secrecy capacity:
  - If two devices can communicate with a high probability guarantee that eavesdroppers cannot hear them, whatever they say is secret
  - BUT how? Probably beamforming!

- Secret messages $\rightarrow$ keys!

  - Secret key generation is now possible using inherent properties of the wireless medium

Further Reading

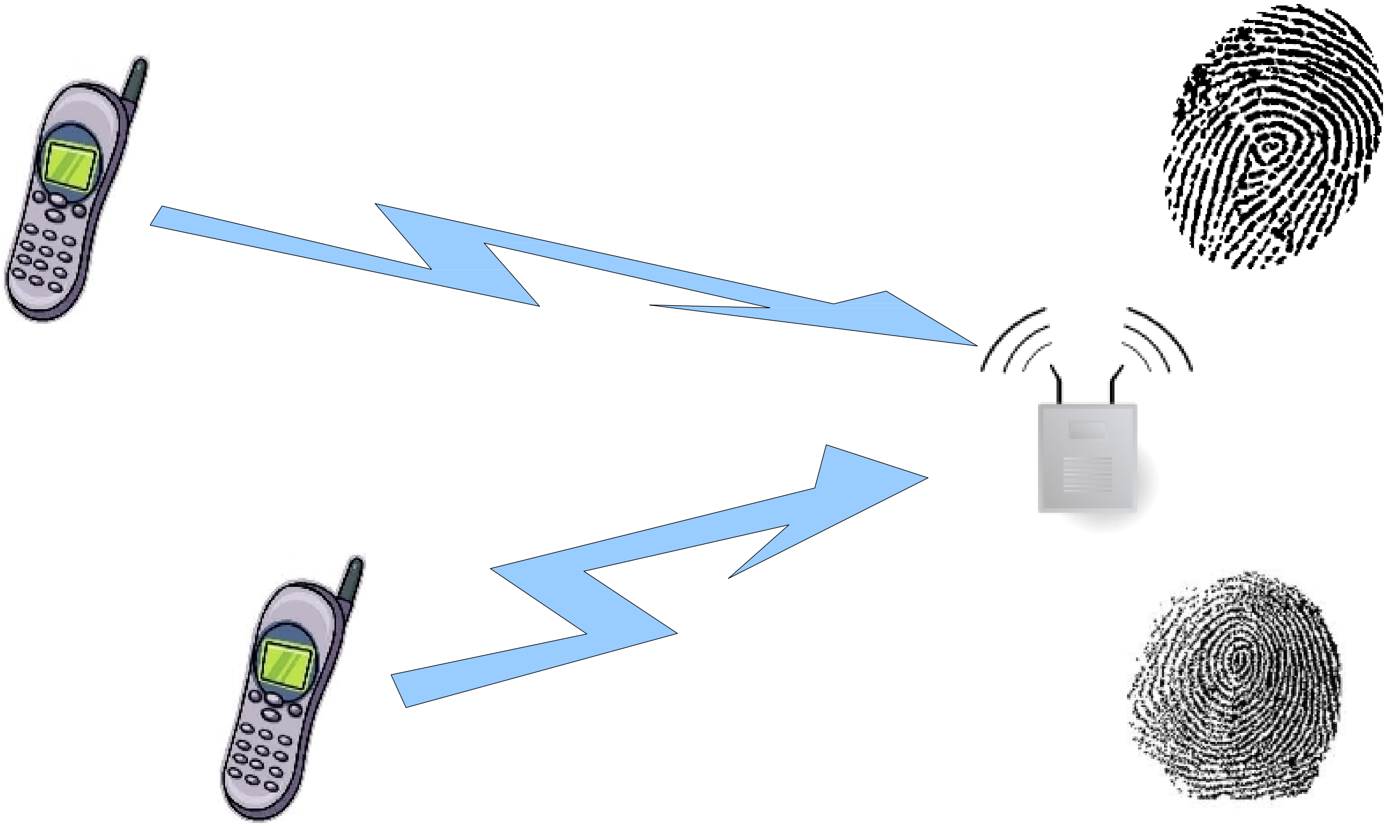
- For a really good summary of secrecy capacity, the formalization, secret key generation, and lots of excellent details:
  - "Physical Layer Security" by Bloch and Barros
    - Available at: https://www.cambridge.org/core/books/physicallayer-security/543CF3D1431805B6AE04A7AA72903D09

More Benefit for the Party?

Physical layer properties can help with authentication!

Diversity of Senders

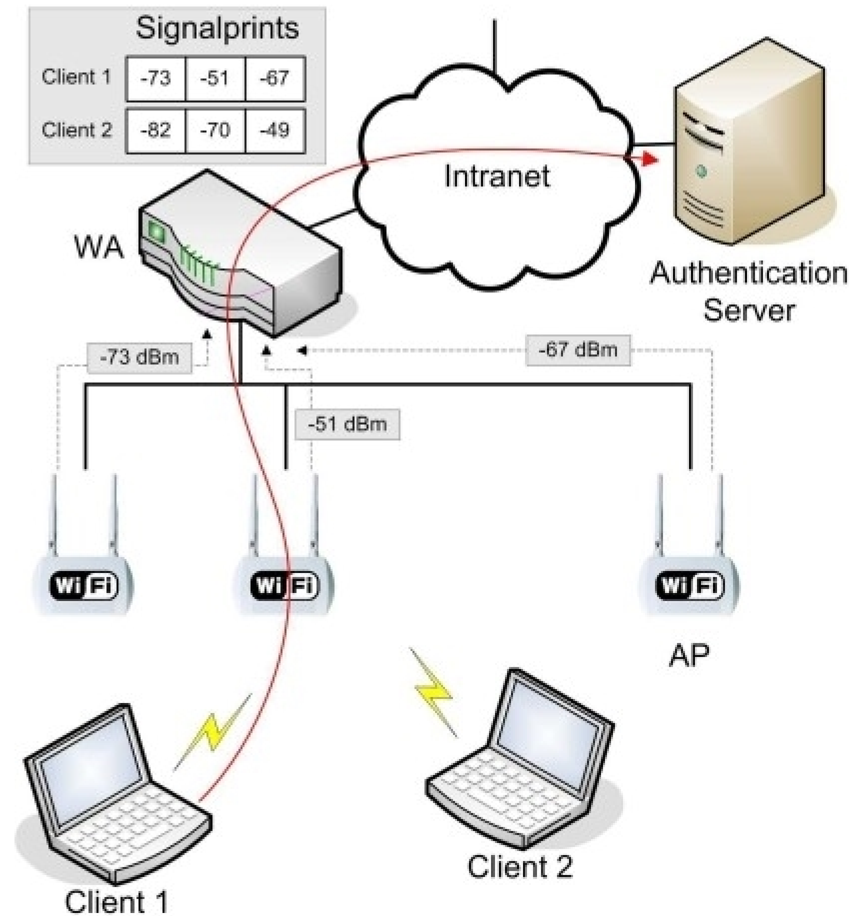
Signals captured by a receiver from senders in distinct locations look “different”



Signalprints

[Faria & Cheriton, WISE 2006]

- In a WLAN with multiple APs, each AP sees different characteristics of packets from each sender
  - Each AP can measure various packet features, some of which are relatively static over packets: e.g., received signal strength
  - A back-end server can collect measurements and keep history of packets from different senders



Signalprint Properties

- Difficult to spoof
  - Spoofing node would require control of medium
  - Transmission power control creates lower RSS at every AP; differential analysis reveals power control
- Correlated with physical location
  - Attacker needs to be physically near target device
- Sequential packets have similar signalprints
  - RSSI values are highly correlated for stationary sender and receiver
    - Note: not highly correlated with distance, but very highly correlated with subsequent transmissions

Limitations

- Signalprints with any reasonable matching rule cannot differentiate between nearby devices
  - Masquerading/spoofing attacks are possible if physical proximity is easily achieved
- Low-rate attacks cannot be detected
  - But, low-rate attacks have limited effects
- Multi-antenna attackers can cheat
- Highly mobile devices can't be printed

Summary

Interference and eavesdropping are two of the most fundamental yet least understood vulnerabilities in wireless.

There's still a lot of work to be done.