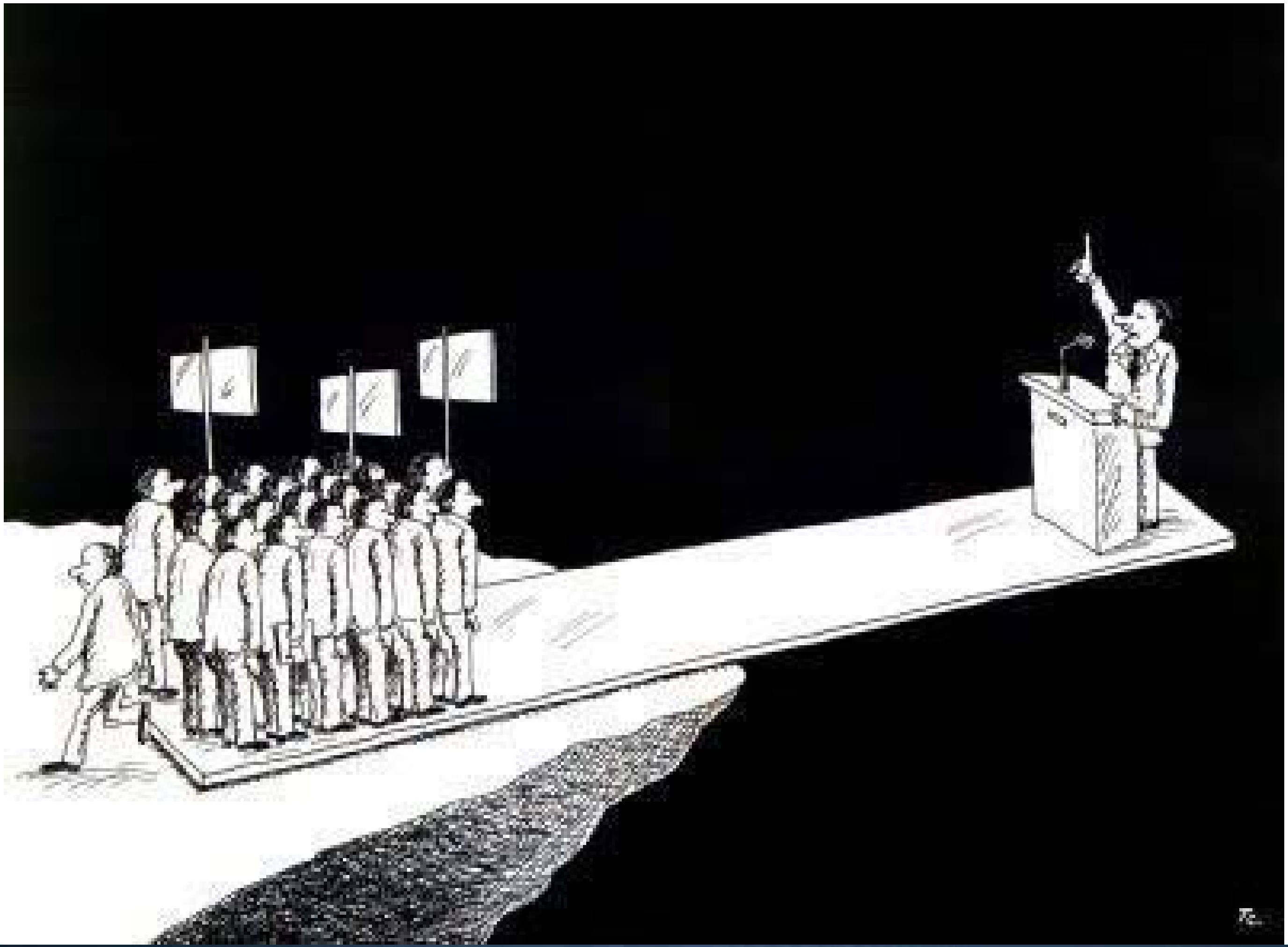
Covert Wireless: Practical LPD-LPI

Resistance is NOT futile



Why Develop Open Covert Communications?

- As an enabler to privacy and liberty
  - Circumvent government restrictions and targeting
  - Political groups, NGOs, demonstrations, war and insurrections
  - Journalists (Marie Colvin)
- Wireless Warrior: a WW II Allied underground radio operator
- Disaster communications
  - Friends and Family
- Affordable/fee-free
- An untapped market: What the intelligence community has today the rich will want tomorrow and many soon after

Why Wireless?

- Infrastructure-less use
- Local, regional and even international links
- Mobility
- No fees

Why NOT wireless?

- Link reliability
- Software immaturity
- Specialized, often non-miniature, antennas
- Only low-speed covert
- Equipment cost
- May not be locally legal

Covert Focus

- Low Probability of Detection/Intercept (LPD/LPI)
- Most reliably implemented at the radio/PHY level

Pros

- No more identifiers available as all transmitted bits obfuscated
- No correlations between requests and replies
- Location privacy

Cons

- Usually not accessible to software developers
- Requires deep understanding of radio and signal processing

What is Covert Communications

- Covert channels
  - Messages hidden within ordinary data (similar to steganography)
  - Never intended for information exchange
  - Can be used to hide encrypted communication
- Signals-based
  - Modulation
  - Coding
  - Directivity (e.g., antenna pattern)
- A complement to encryption which is often used in tandem

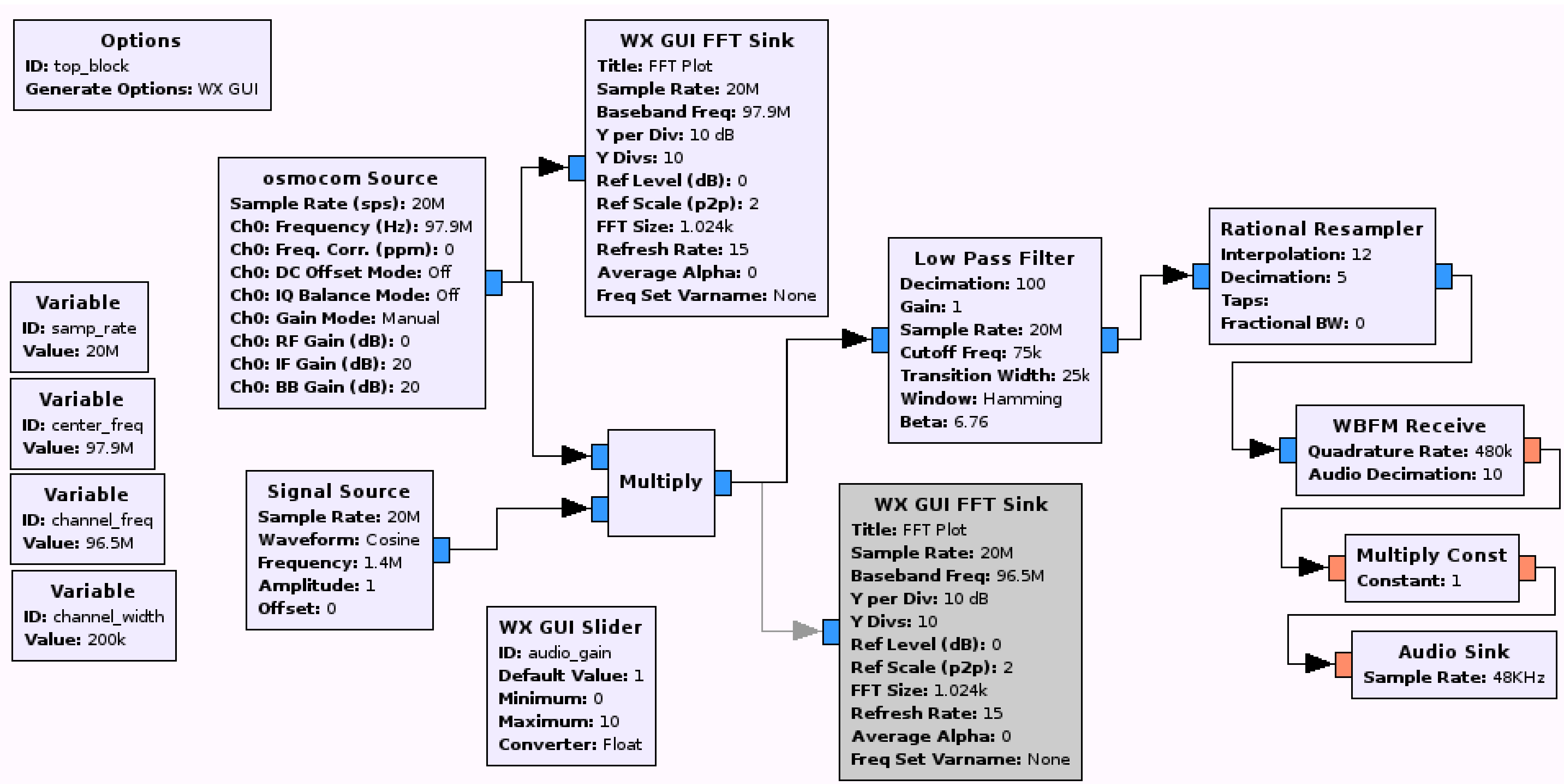
SDR and Gnu Radio Changed Everything

- Before SDR radio design only for large entities and RF engineers
- First SDRs were expensive commercial and proprietary
- Gnu Radio, created to make FOSS radio practical and affordable, is now mature
- Special signal capture and generator devices make SDR practical
- SDR receivers common
  - RTL dongles ~$20 USD
  - FunCube covers LF-UHF
- Transceivers less so, (e.g., HackRF One and USRP)
- Proper COTS transmitter configurations (SDR + amp) outside of ham gear needed

Gnu Radio

- Free & open-source toolkit
  - (GPL) version 3
- Signal processing blocks to implement software radios
  - With low-cost external RF hardware or in a simulation environment
- Mature: widely used in hobbyist, academic and commercial environments
- C++ and Python APIs
- For computation intensive parts C++/VOLK = (vector-optimized library of kernels)
- GR Companion: GUI IDE for prototyping applications

GnuRadio Companion Example: FM Receiver



HackRF One

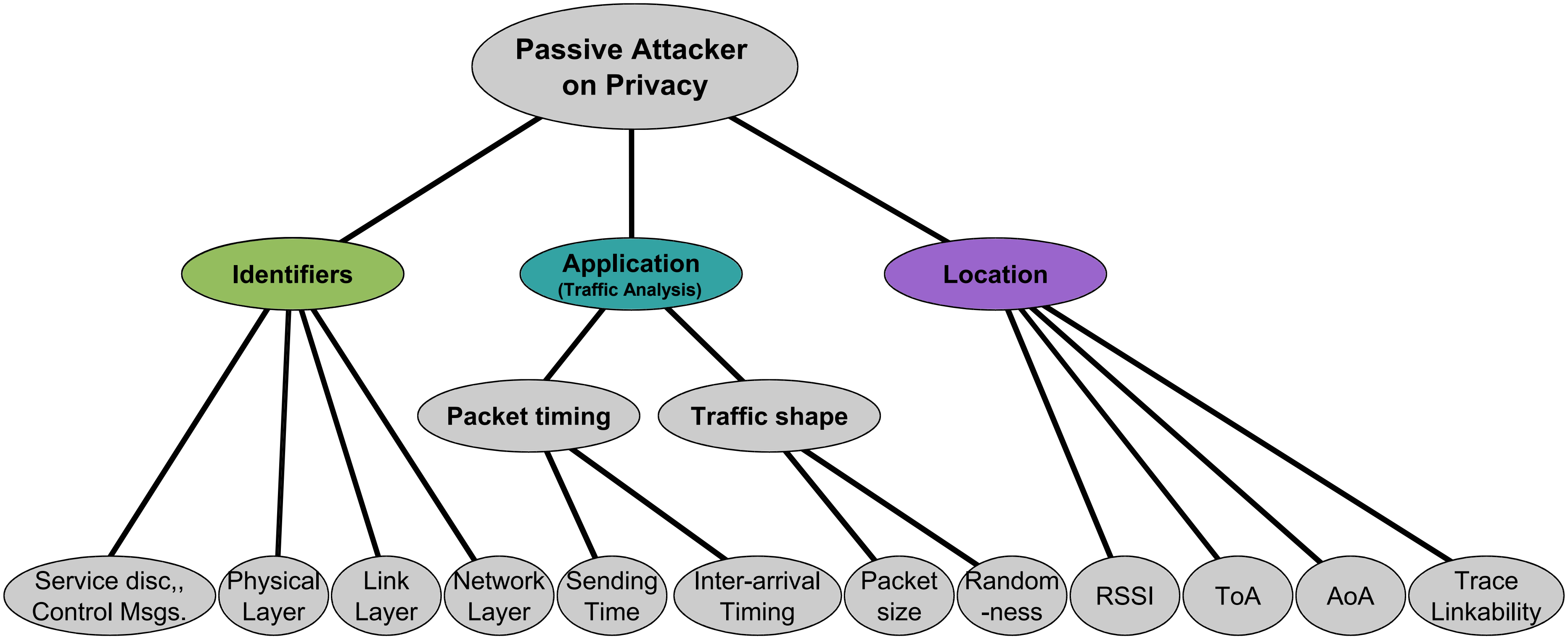
- ~1 MHz to 6 GHz coverage
- Half-duplex transceiver
- Up to 20 MSPs
- Nominal 10 mW transmitter
- **8-bit quadrature samples I/Q**
- Compatible with GNU Radio, SDR#, and more
- Software-configurable RX and TX gain and baseband filter
- Powered antenna port
- USB peripheral or stand-alone
- Clock input and output for synchronization
- Programmable buttons
- Internal pin headers for expansion (e.g.,up to 16-bit A/D or FPGA)
- Hi-Speed USB 2.0 powered
- Open source firmware and hardware

Wireless Threats

- Passive
  - Signal analysis
    - Type, frequency, bandwidth, etc.
    - Where - Location Privacy?
  - Traffic Analysis
    - Who's communicating with whom?
    - When is someone communicating?
  - Eavesdropping
    - What is the content of their communication?
- Active
  - May mean you are targeted!
  - Jammers
    - Block Communications
    - Force Insecure Reversion
  - Man-in-the-Middle
  - Black-bag intrusion

Passive Threats

- Many potential privacy leaks of wireless communication protocols for a passive attacker

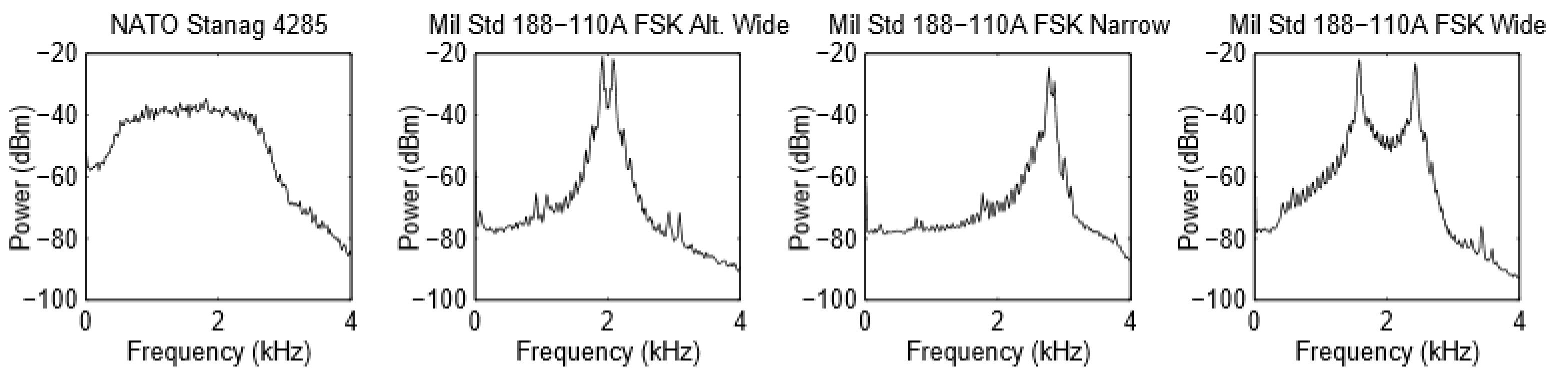


Signal Features Targeted

- Common emission sources and types
  - Frequency, location, time and (if possible) content
- Red October Crawler/Seismic scenario
  - Unusual modulation/coding
  - Transmitter physical layer fingerprinting
  - Code/symbol rate signatures

Signal Tech They Are Using

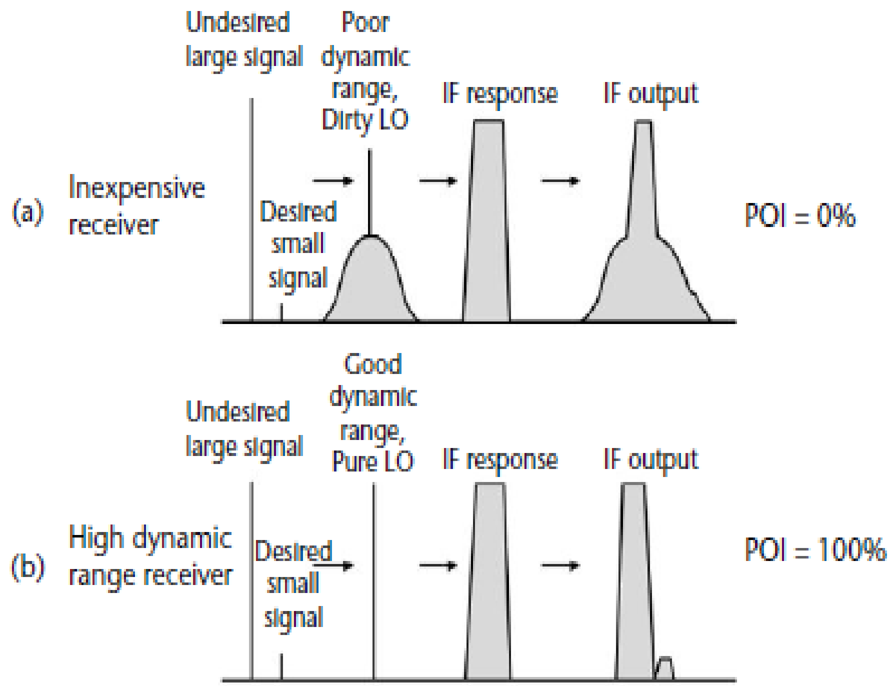
- Feature Extraction
  - Instantaneous amplitude
  - Phase variance
  - Spectral symmetry
  - Transmission models
  - Higher order statistics
- Classification association
  - Threshold detection
  - Artificial neural networks
  - Pattern recognition algorithms



High Probability Of Intercept (HPOI) Receivers

- Purpose: Capture as much RF spectrum as quickly as possible with the highest frequency resolution and dynamic range.
- Probability of Intercept (POI) % = probability to detect, process, and identify an emitter within a specified time

- Example
  - A weak CW signal hidden in the side-bands of a strong signal and close frequency

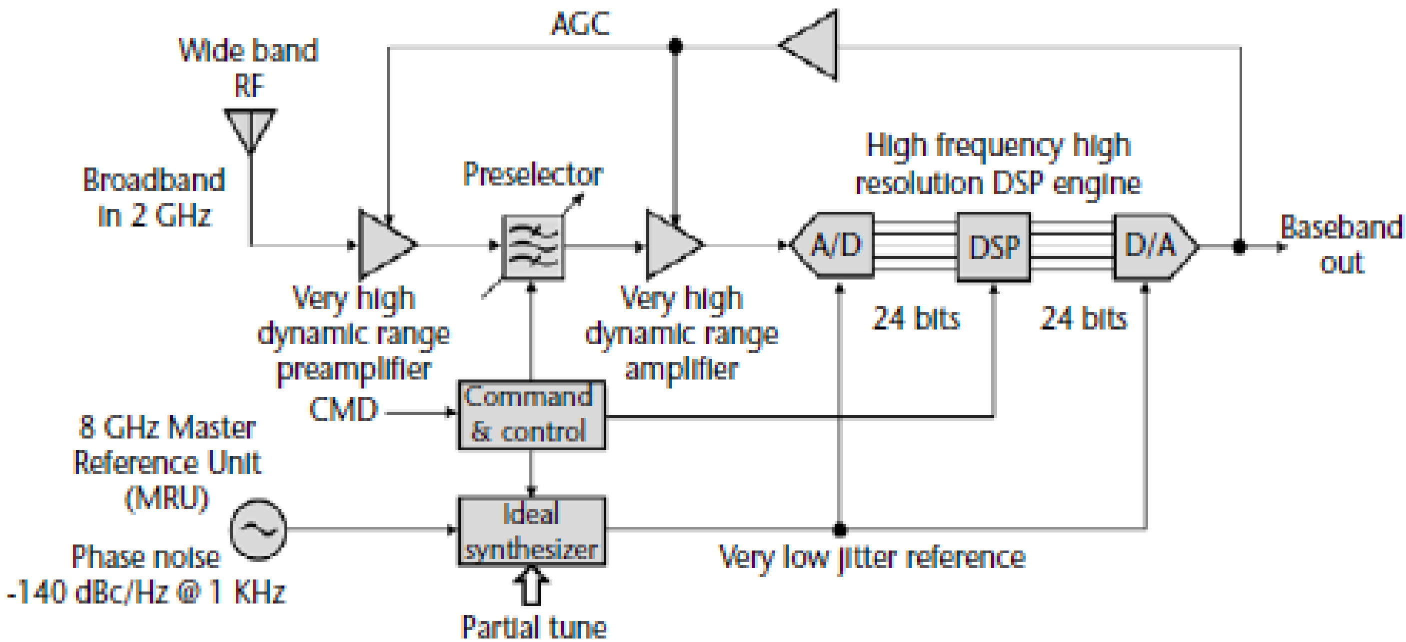


POI Factors

- A priori signal knowledge
  - **Prevention is key to covert**
  - Frequency and modulation
  - Probable location
  - Bandwidth and coding
  - Transmission time(s)
  - Repetition rate
  - Antenna (e.g., pattern)
- HPOI design elements
  - Dynamic range
  - LO and synthesizer quality
  - Noise figure & Compression points
- Capture likelihood
  - Emitter's vs. receiver's beam width
  - Emitter pulse width
  - Instantaneous bandwidth
  - Receiver sensitivity, resolution, dwell time, scan time
  - SIGINT system throughput
  - Reaction time constraints
  - Emitter parameter validation
  - Channel conditions (e.g., number of emitters/Hz &QRM)

HPOI Designs

- Ideal HPOI Receiver
  - SDR on steroids
  - Cognitive radio: recognize & adapts to received information
  - **Wanted a GR HPOI**
- Limitations
  - A/D speed – dynamic range
  - Synthesizers/oscillators
  - Band/channel conditions



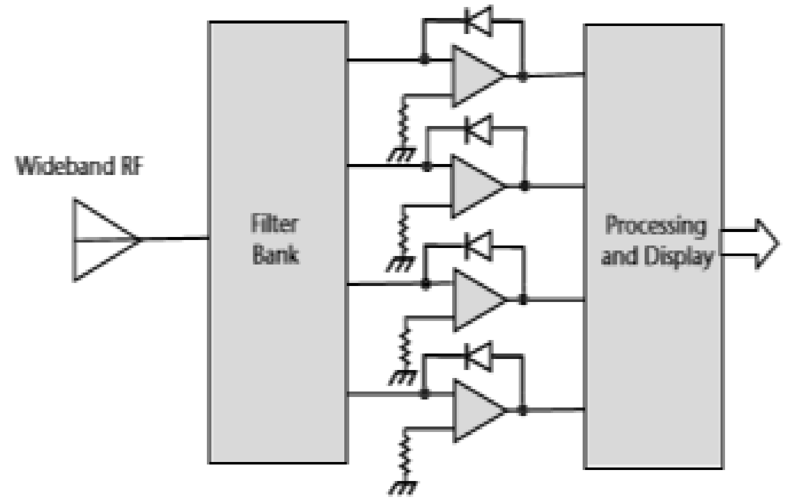
Common Electronic Warfare Receivers

- Crystal video—warning receiver
- Instantaneous frequency measurement (IFM)
- Phase detection—used for direction of arrival
- Ultra-wideband scanning superheterodyne
- Channelized receiver—activity monitor
- Bragg cell—activity monitor
- Combinations of the above

Crystal Video Receiver

- A form of a tuned radio frequency (TRF) receiver
  - Splits a wide input frequency range into several broad contiguous bands, which are
  - Filtered and logarithmically amplified before detection
- Simplest electronic counter measures (ECM) receiver
- Usually used as warning (police) radar receivers

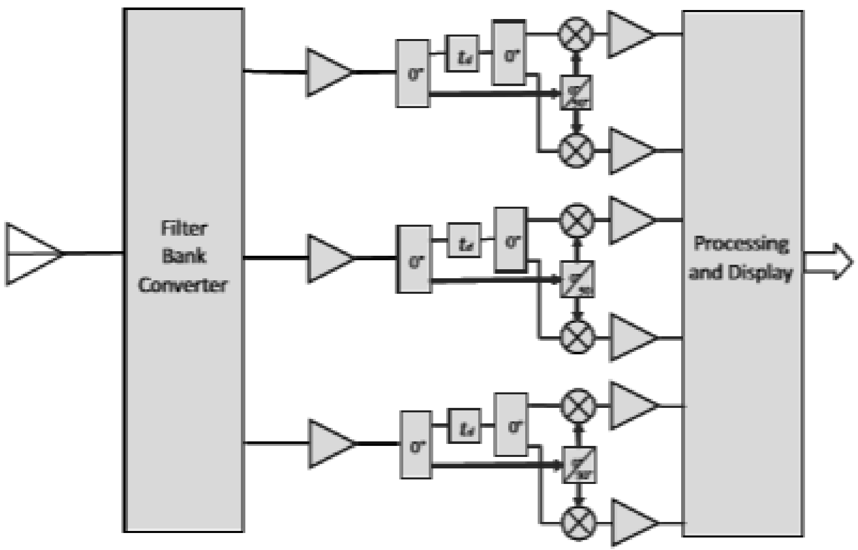
- Low cost and small but
  - Low sensitivity due to a large noise bandwidth, and
  - Subject to blocking from strong in-band signals.



Instantaneous Frequency Measurement (IFM)

- A more complex form of the TRF receiver, using
  - Bandpass/band-reject front-end filters +
  - Delay lines and phase detectors
- Near instantaneous frequency measurement of single pulse signatures

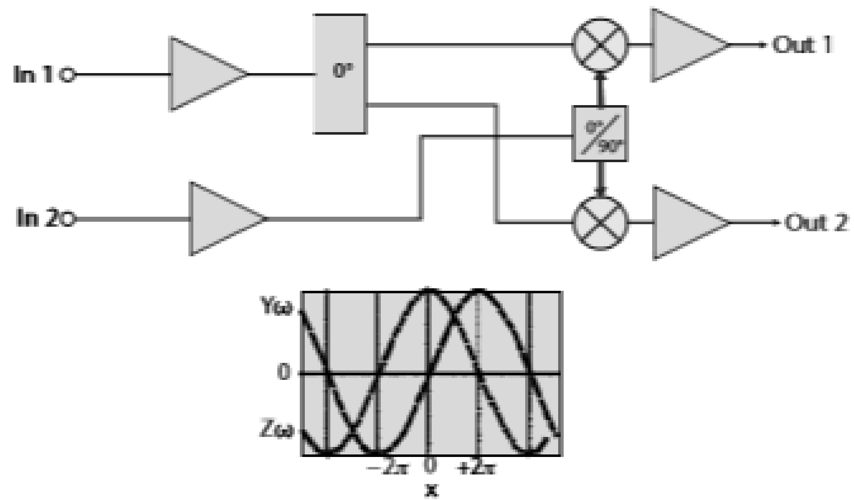
- For jammer quick set-on or
- Acquisition receiver to set up a slower, narrowband, high-resolution receiver



Phase Detection in Interferometer Receivers

- Not strictly considered a type of receiver but
- An important discriminator type used in interferometer receivers
- Used for direction finding

- Typical phase detector arrangement used in an interferometer receiver



Swept Superheterodyne Receivers (SSR)

- Wideband
  - Fast sweeping/hopping wide IF bandwidth receiver
  - FFT directly at the IF and
  - >1 GHz, center frequency, bandpass A/D-DSP
  - Complex auto-switched half-octave front-end filters
- Narrowband
  - Wideband SSR + narrowband second or third IF sweeping through the first very wide bandwidth IF for increased resolution
- Typical Performance

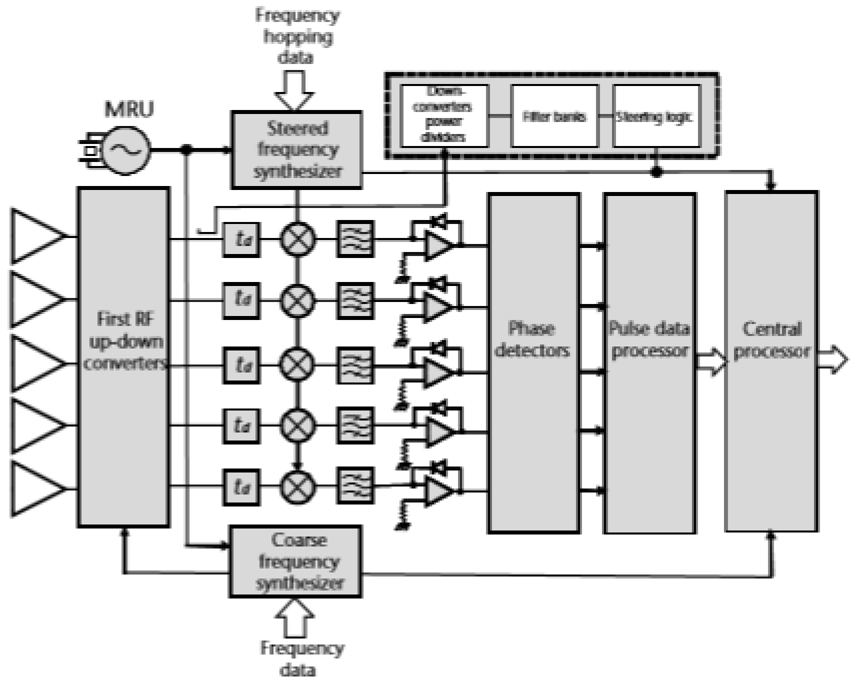
Total bandwidth	2 to 18 GHz
IF center frequency	1 GHz typical
Front end composite	8 half-octave filter bank
Instantaneous bandwidth	1 GHz typical
Ultimate resolution	Limited by A/D
Linear dynamic range	>100 dB typical
MDS	−110 dBm typical
POI	<100% near instantaneous

Total bandwidth	2 to 20 GHz
Double conversion superheterodyne	First IF: 1.5 GHz typical, second IF: 0.5 GHz typical
Front end composite	7 half-octave filter bank
Instantaneous bandwidth	>0.5 GHz typical
Ultimate resolution	10/100 Hz typical
Linear dynamic range	>130 dB
MDS	−138 dBm typical
POI	<100% not instantaneous

Channelized Bulk Filter (Cued) Receiver

- A multiple superhet
  - Divides the frequency range into contiguous channels
  - Parallel receiver architecture with a wide input bandwidth and multiple narrowband outputs
- Features
  - Wider bandwidths monitored at each coarse frequency step
  - 2-20-GHz band scanned in 36 steps instead of 1,800 steps for a 10-MHz IF bandwidth
  - Reduces scanning time and greatly increases POI

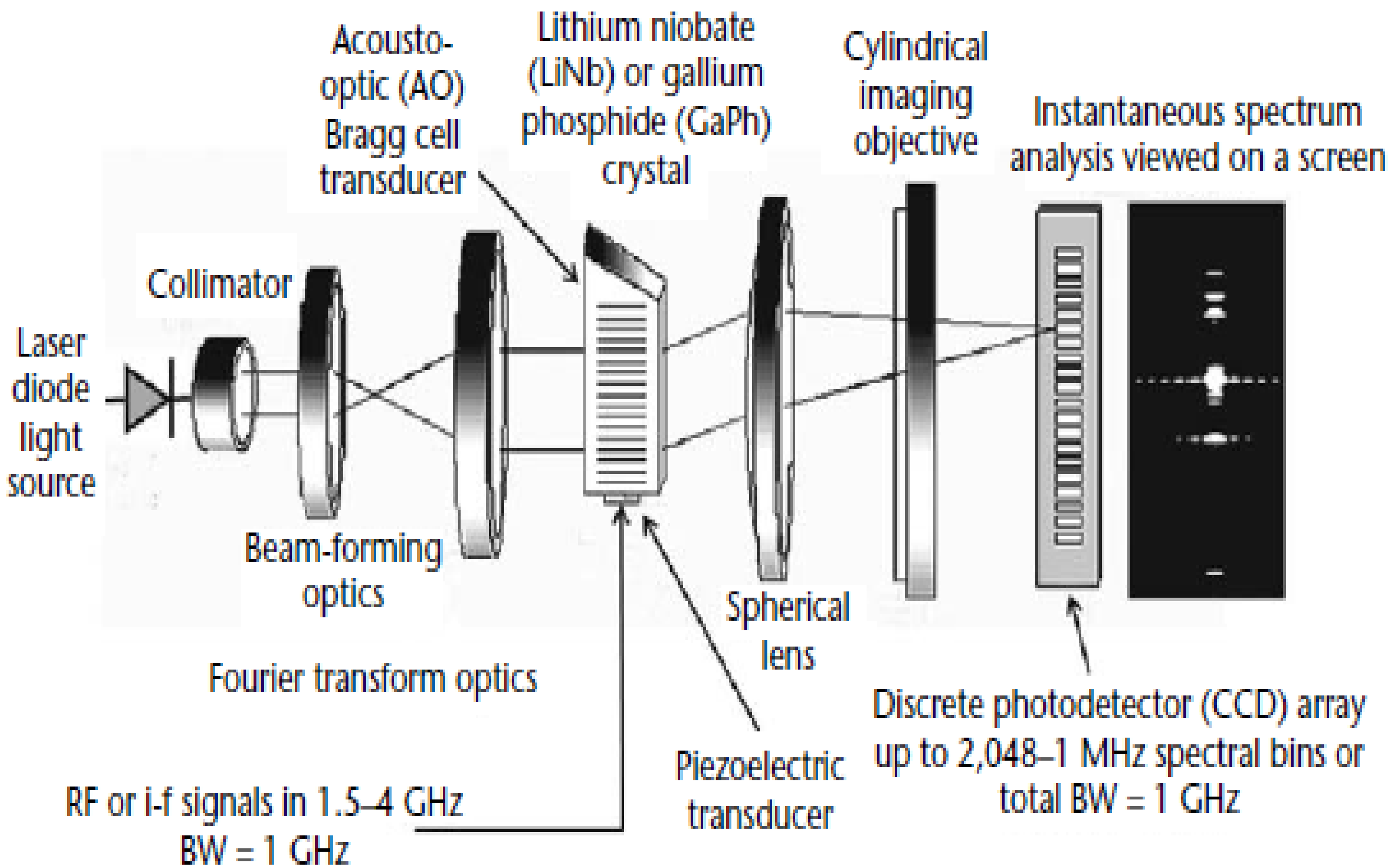
Total bandwidth	2 to 20 GHz
Instantaneous bandwidth	0.5 GHz typical
MDS	−85 dBm typical
Pulse width resolution	100 ns typical
Signal resolution	10 MHz minimum, 30 MHz for a 50-dB signal separation
Frequency accuracy	+/− 2 MHz pulse-to-pulse
Data throughput	1 Mpps
POI	<100%



Bragg Cell Receiver

- Originally from radio astronomy
  - Ultra-wide-band instantaneous receiver
  - Blends RF and photonic technologies (acousto-optic modulator)
  - Can be used to steer much higher resolution receivers, or
  - Replacement for state-of-the art A/D converter technology receivers
- Pros
  - No variable LO required for resolution over the bandwidth of interest
  - Allows simultaneous HPOI of many signals (e.g., crowded band)
- Cons
  - Limited linear spurious-free dynamic range (*may* not very effective against some broadband, very low spectral energy, signals especially under crowded band conditions)

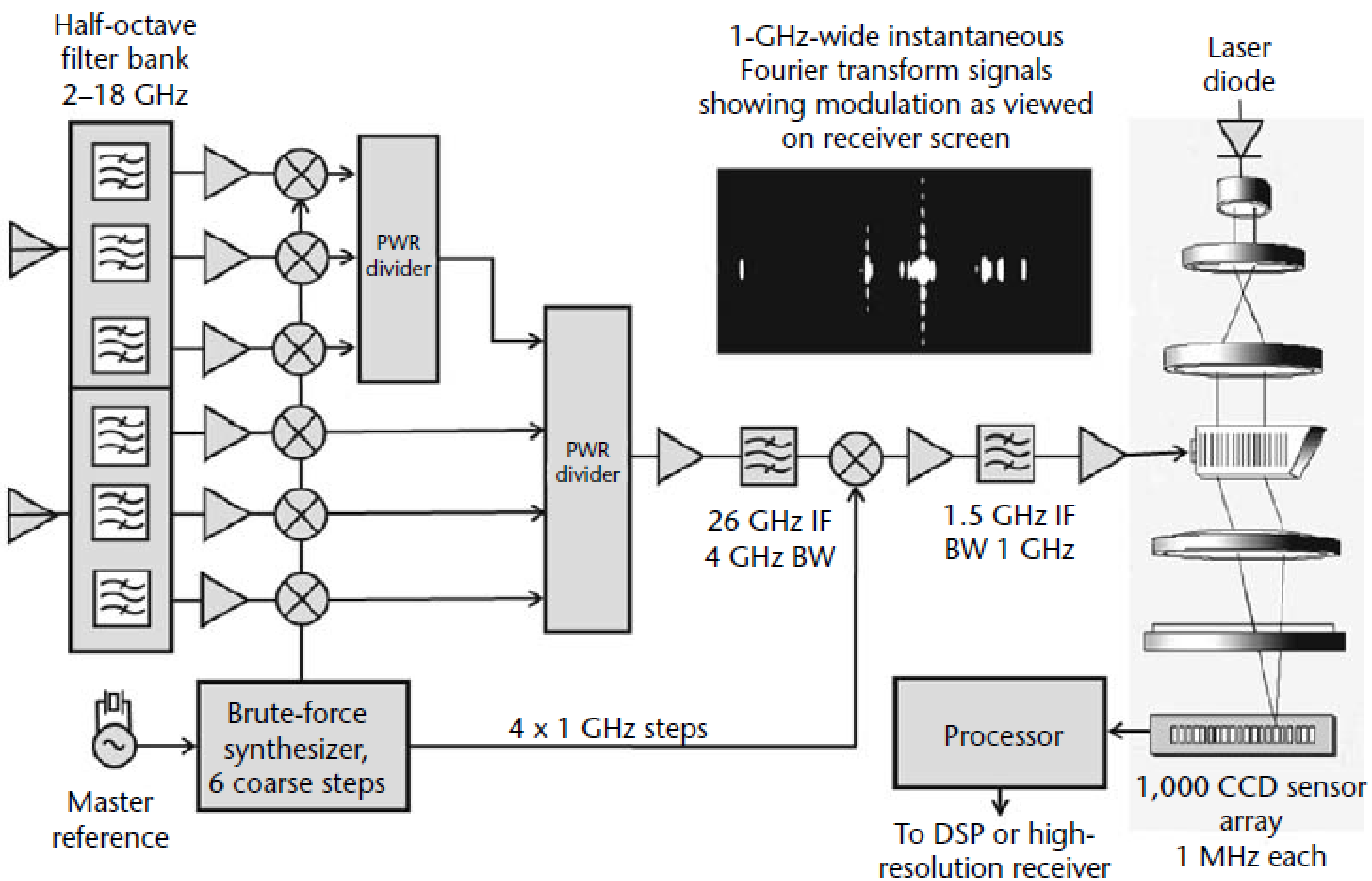
Bragg cell receiver principle



Commercial Bragg Cells

- Single cell (256 frequency spots)
- Bragg cell assembly
  - 16 channels 180 MHz each
  - 1 GHz composite bandwidth
  - 20 spots/channel
  - 2 watts of RF drive/channel
  - Laser wavelength is 355 nm

EW Bragg Cell Receiver



Active Threats

Jammers

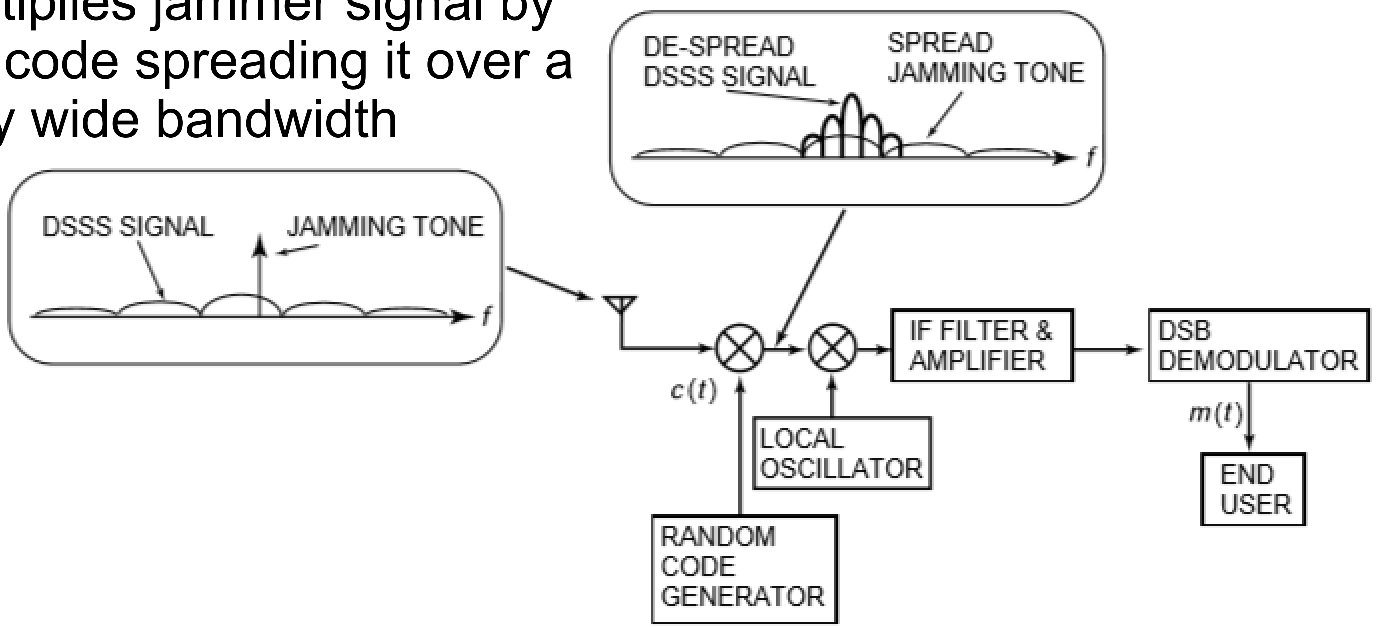
- Detecting a jammer is challenging because there exist numerous intelligent jammer strategies
- Either blocks the source from sending packets or the receiver from receiving legitimate packets
- Performance indices/measures
  - JSR (Jammer-to-Signal Ratio)
  - PSR (Packet Send Ratio): creating congestion to cause sender's network interface packet buffer to drop packets
  - PDR (Packet Delivery Ratio)

Jammer Types

- Repeat-back (Multipath)
  - DSSS largely immune as autocorrelation of spreading code typically very small for time delays greater than one chip time
- Partial-band
- Broadband
  - Additive White Gaussian Noise (AWGN)
- Multitone
- Pulse
- Packet jammer
  - Sends initiation data packets in a loop to capture receiver's state machine

CW and Multitone Jammers

- DSSS has relative immunity
  - Despreading mixer collapses the DSSS signal back to a NB signal
  - Multiplies jammer signal by PN code spreading it over a very wide bandwidth
- Majority will fall well outside the passband of the IF filters, significantly decreasing the JSR at the demodulator



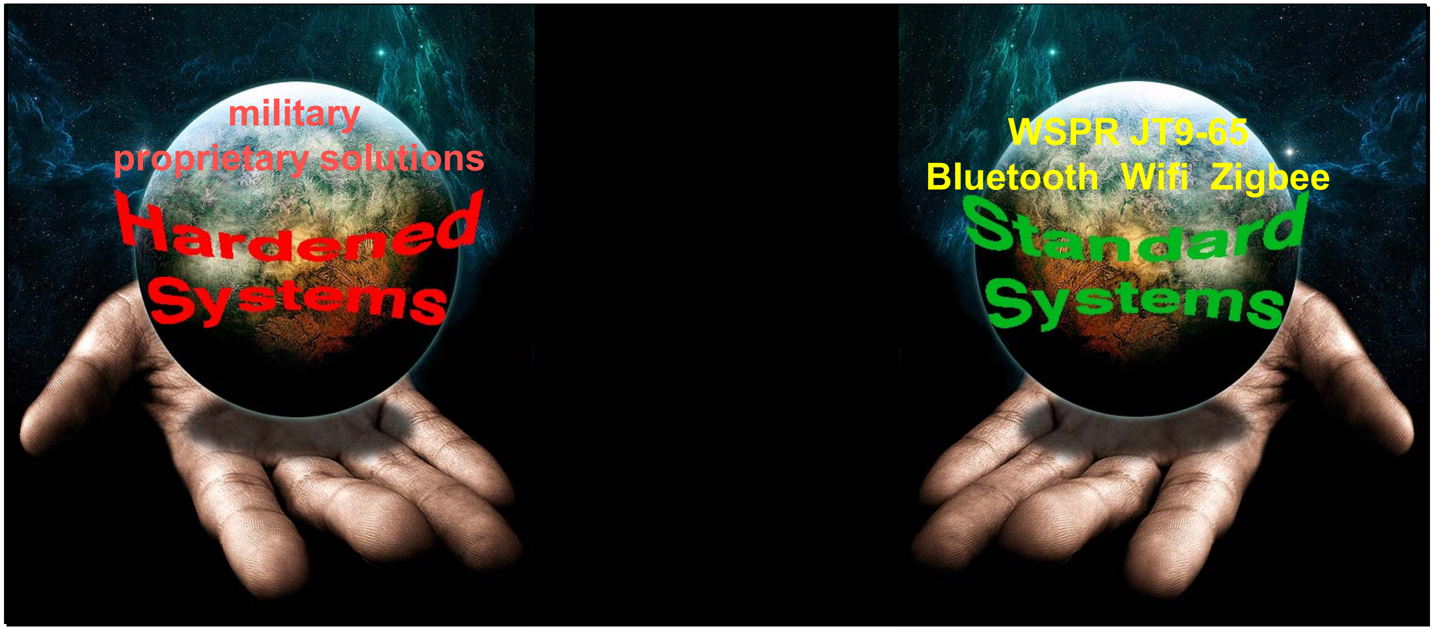
Fortune Favors the Prepared

- Intel agencies have huge resources & experience
- But monitoring all wireless communications is still a Sisyphean task
- Defender must counter all exploits, attacker must only find one and exploit: works for intel and adversaries
- Physics and HPOI receiver constraints are like Zero-Days that cannot be fixed
- Unless targeted, those using good covert communications and trade-craft, are in minimal danger

Good OPSEC

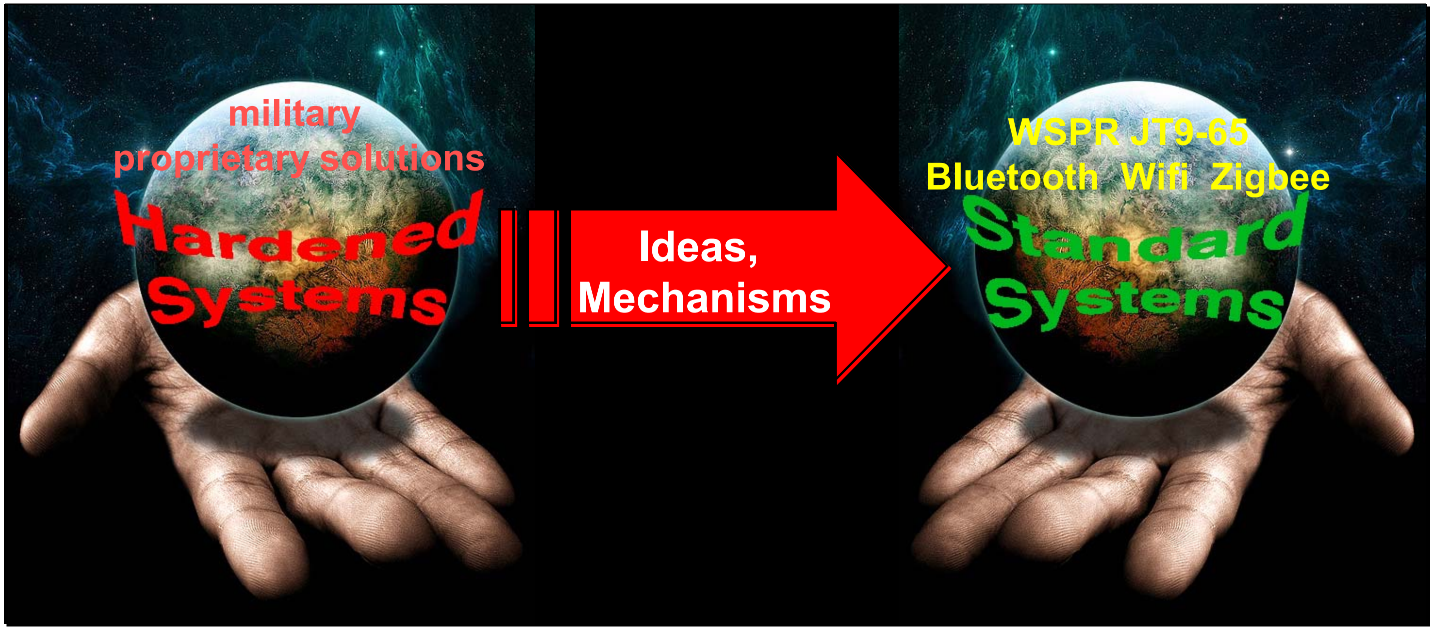
- … means hiding in plain sight
- Invisible to neighbors and average citizens
- “Plausible deniability”
- Not this -->

Where To Look For Solutions



- Hardened Systems:
  - Specialized
  - High security and privacy
  - High costs
  - Proprietary and hard to get
- Open Systems:
  - Standardized/Open source
  - Low security and privacy
  - Low costs
  - High interoperability

Where To Look For Solutions (con't)



- **Goal:** Harden open/standard wireless communication protocol(s) to increase the users "privacy"
- **Conditions:**
  - Based on an open source/standards
  - Using OS Software Defined Radio (SDR)

Informational
Identification
Communication Relationships
Location

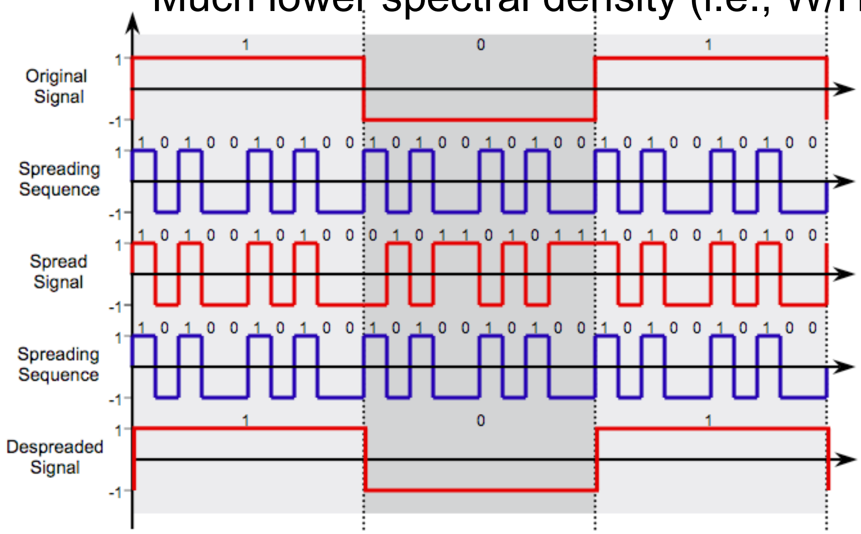
Major LPD/LPI methods

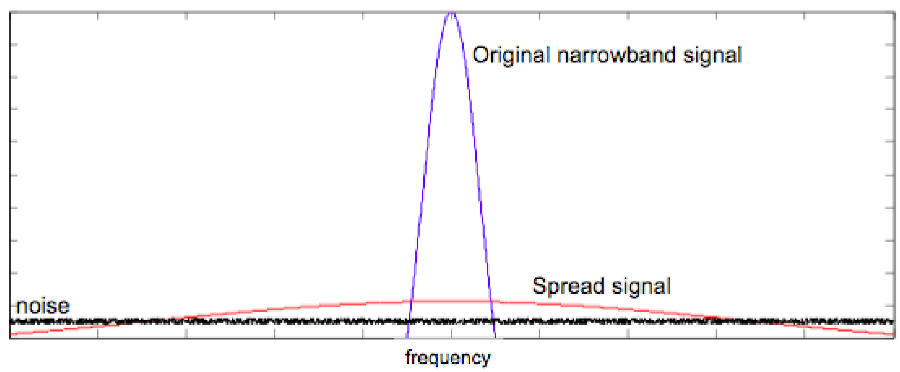
- Hide the Signal below the noise (Spread spectrum/UWB, chaotic and QRP)
- Hide the Signal within or below a cover signal or data (Steganography)
- Alice selectively blocks Bob's Signal to thwart Eve (Controlled jamming)
- Greatly reduce narrow-beam off-axis reception (Side-lobe suppression)
- Re-purpose widespread commercial service

Hiding the Signal below the Noise

Direct Sequence Spread Spectrum

- Information spread to a bandwidth much greater than required for transmission
- Spreading by modulating each information bit on a spreading sequence (chips)
  - Spreading sequence independent of data
  - **Narrowband signal spread to a broadband signal**
  - Much lower spectral density (i.e., W/Hz)

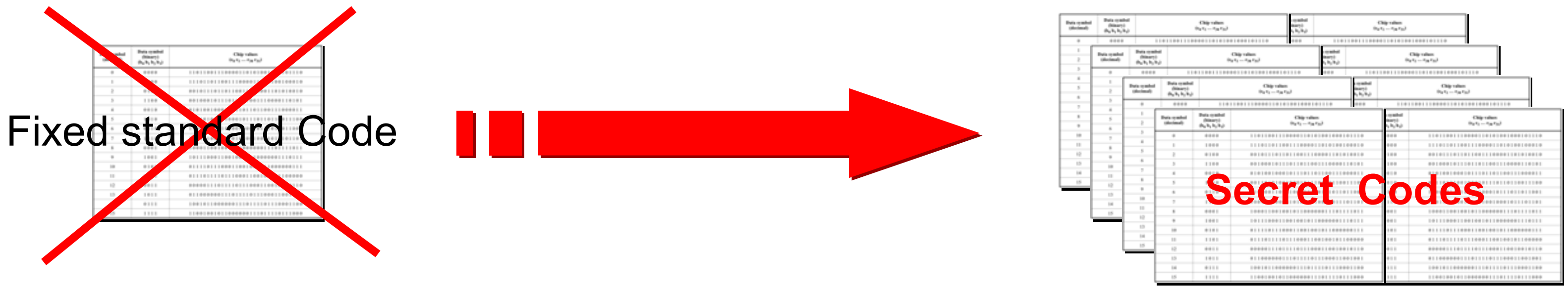




- **Benefits:** anti-jamming, anti-interference, **possible low probability of detection/intercept**, uncoordinated frequency reuse (e.g. CDMA)

Hiding the Signal Below the Noise Approach #1

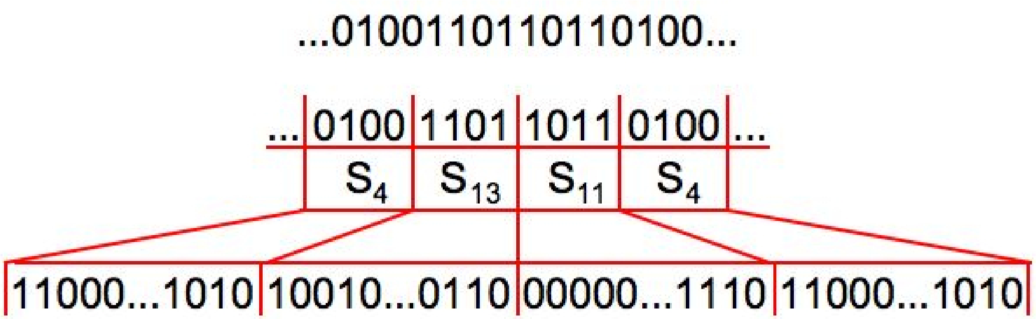
Idea: Secret & random symbol-to-chip table dynamically changing

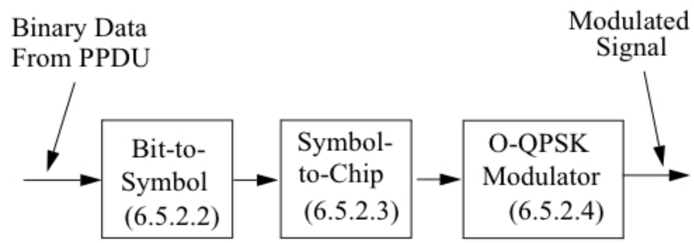


- Obfuscate all transmitted data at the lowest possible layer (PHY)
- Maximize LPD/LPI properties of DSSS

M-ary Spread Codes

- Example: 16-ary Direct Sequence Spread Spectrum technique and O-QPSK modulation (16 spreading sequences, not only one!)

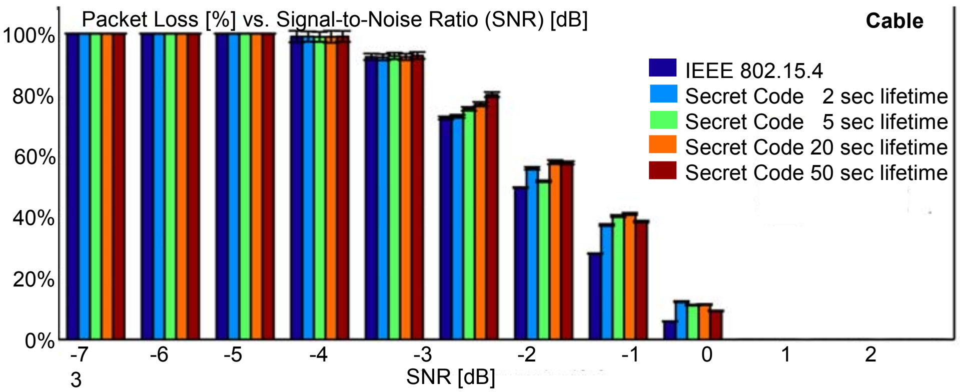


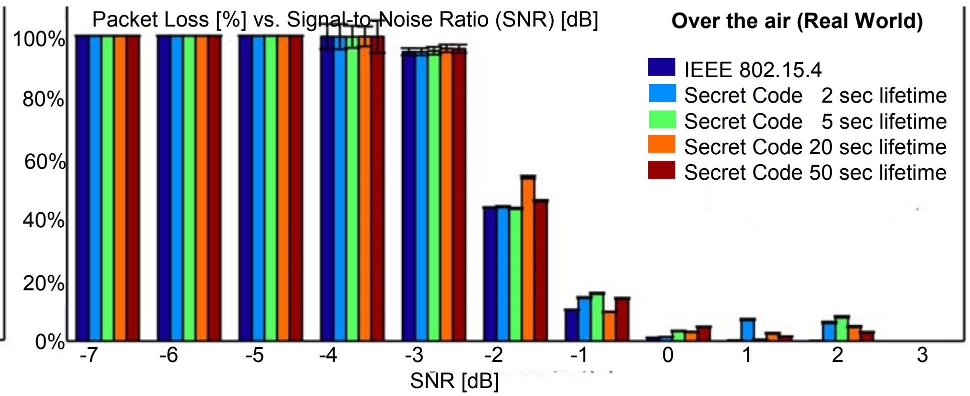


Data symbol (decimal)	Data symbol (binary) (b_0 b_1 b_2 b_3)	Chip values (c_0 c_1 ... c_{30} c_{31})
0	0 0 0 0	1 1 0 1 1 0 0 1 1 1 0 0 0 0 1 1 0 1 0 1 0 0 1 0 0 0 1 0 1 1 1 0
1	1 0 0 0	1 1 1 0 1 1 0 1 1 0 0 1 1 1 0 0 0 0 1 1 0 1 0 1 0 0 1 0 0 0 1 0
2	0 1 0 0	0 0 1 0 1 1 1 0 1 1 0 1 1 0 0 1 1 1 0 0 0 0 1 1 0 1 0 1 0 0 1 0
3	1 1 0 0	0 0 1 0 0 0 1 0 1 1 1 0 1 1 0 1 1 0 0 1 1 1 0 0 0 0 1 1 0 1 0 1
4	0 0 1 0	0 1 0 1 0 0 1 0 0 0 1 0 1 1 1 0 1 1 0 1 1 0 0 1 1 1 0 0 0 0 1 1
5	1 0 1 0	0 0 1 1 0 1 0 1 0 0 1 0 0 0 1 0 1 1 1 0 1 1 0 1 1 0 0 1 1 1 0 0
6	0 1 1 0	1 1 0 0 0 0 1 1 0 1 0 1 0 0 1 0 0 0 1 0 1 1 1 0 1 1 0 1 1 0 0 1
7	1 1 1 0	1 0 0 1 1 1 0 0 0 0 1 1 0 1 0 1 0 0 1 0 0 0 1 0 1 1 1 0 1 1 0 1
8	0 0 0 1	1 0 0 0 1 1 0 0 1 0 0 1 0 1 1 0 0 0 0 0 0 1 1 1 0 1 1 1 1 0 1 1
9	1 0 0 1	1 0 1 1 1 0 0 0 1 1 0 0 1 0 0 1 0 1 1 0 0 0 0 0 0 1 1 1 0 1 1 1
10	0 1 0 1	0 1 1 1 1 0 1 1 1 0 0 0 1 1 0 0 1 0 0 1 0 1 1 0 0 0 0 0 0 1 1 1
11	1 1 0 1	0 1 1 1 0 1 1 1 1 0 1 1 1 0 0 0 1 1 0 0 1 0 0 1 0 1 1 0 0 0 0 0
12	0 0 1 1	0 0 0 0 0 1 1 1 0 1 1 1 1 0 1 1 1 0 0 0 1 1 0 0 1 0 0 1 0 1 1 0
13	1 0 1 1	0 1 1 0 0 0 0 0 0 1 1 1 0 1 1 1 1 0 1 1 1 0 0 0 1 1 0 0 1 0 0 1
14	0 1 1 1	1 0 0 1 0 1 1 0 0 0 0 0 0 1 1 1 0 1 1 1 1 0 1 1 1 0 0 0 1 1 0 0
15	1 1 1 1	1 1 0 0 1 0 0 1 0 1 1 0 0 0 0 0 0 1 1 1 0 1 1 1 1 0 1 1 1 0 0 0

- **Normally publicly known** symbol-to-chip table used by all

Evaluation: Packet Loss





- Left: Cable

Right: Over the air (real world scenario)

- Random Codes compared to nearly orthogonal Code from IEEE 802.15.4 standard:
  - No minimum distance between chip-sequences of a Code
- PER increase below 13 %

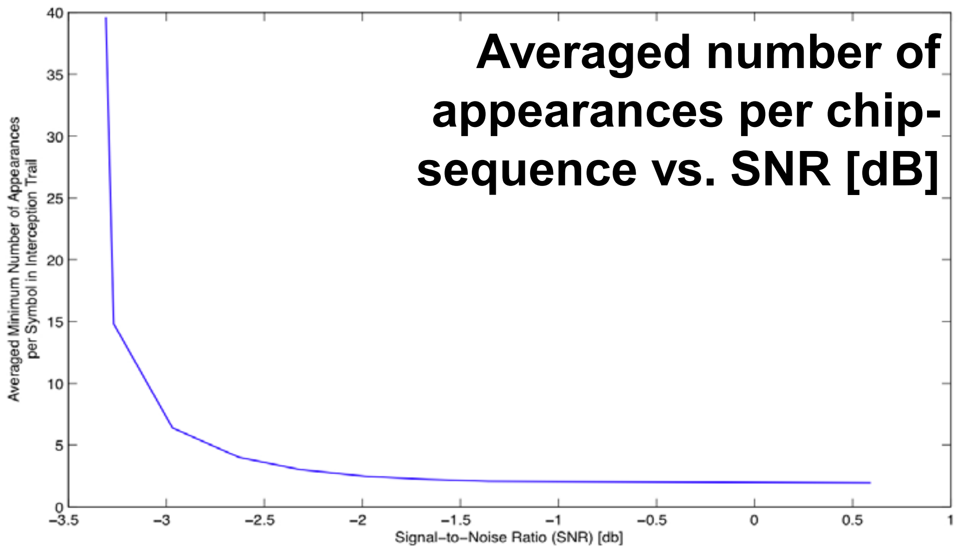
Attacking the Secrecy of the Codes

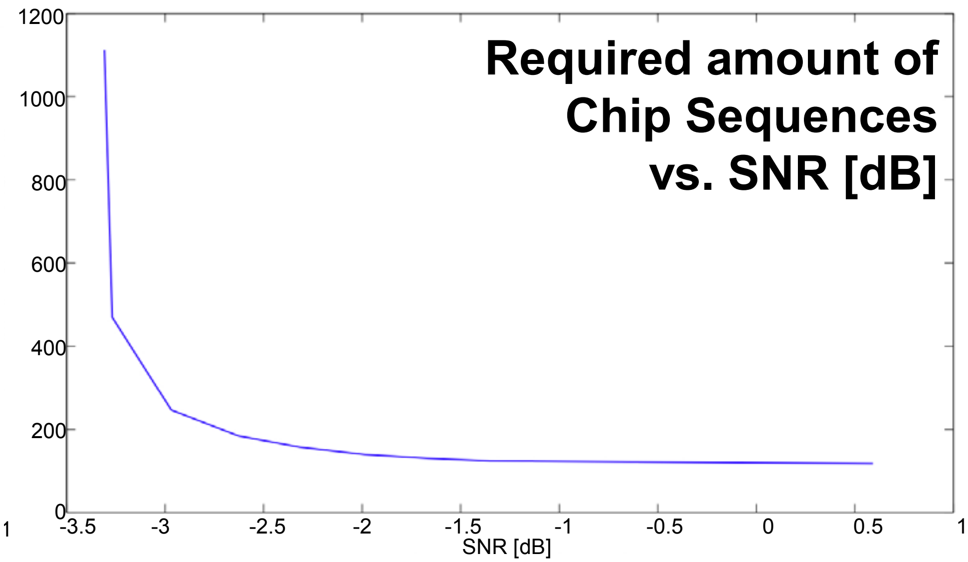
- Worst Case Attacker:
  - Protocol parameters assumed to be known (its FOSS)
  - Adapted m-ary DSSS attack [Wang, ICC, 2008]

- Attacker Strategy:
  1. Record chip stream from channel
     As synchronization assumed this results in a list of intercepted chip-sequences
  2. K-means Clustering to eliminate chip errors
  3. Collect centroids / compare with true codes

➔ **Measure** performance of attacker
➔ Determine **how often each individual chip sequence is needed**
➔ Determine **required amount of chip sequences**

Attacking the Secrecy of the Codes





- The lower the SNR (the higher the chip error rate) the more often each individual chip sequence is required
- Asymptote:
  - No Chip Errors → each once
  - E[each Chip Seq. received once] ≅ 54 (if uniform distributed)

- Need **Code Change every packet** to defend against Worst Case Attacker

→ *b* ≤ 27 bytes

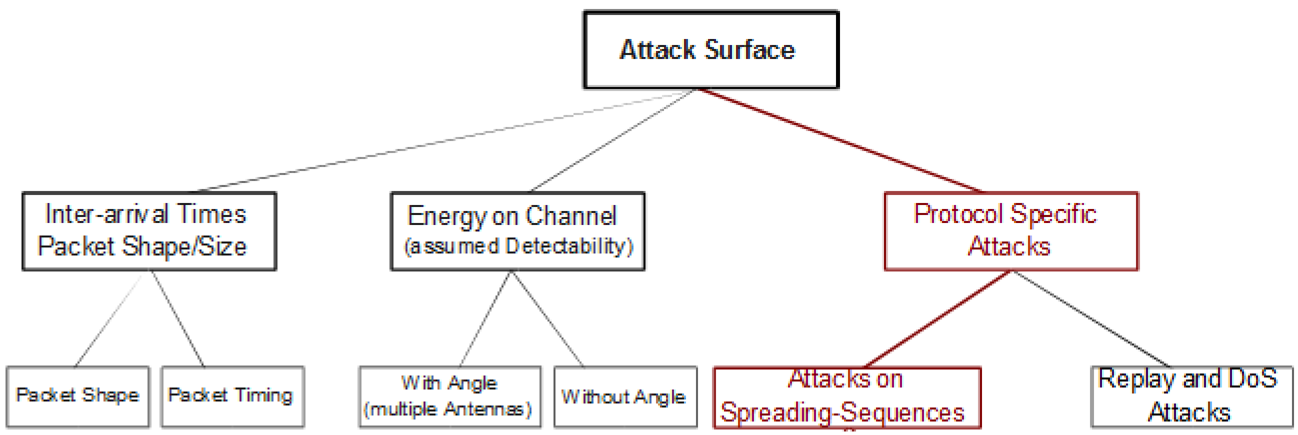
→ Code Change every packet (average packet size of 22 bytes)

Evaluation: Secret Codes

- Initial protocol tests using GnuRadio SDR
  - Secret and dynamically changing but only 32-bit codes instead of the publicly known 16-bit codes in 802.15.4
- Packet Error Rate increase < 13%
- Protocol overhead < 1%
- Worst Case Attacker requires **only 27 bytes** to break the secrecy of the Codes

Possible Ways to Decrease PHY Attack Surface

- Combine DSSS + FH
- Cryptographic primitive changes
- Entropy maximization of packet timings and size and dynamic spreading factor
- Burst frame improvements



Low Detectability

- Often cited attribute for SS and CDMA
  - Only valid if spread code and/or seed remain secret
  - Static PRNG seeds may be discovered by theft or tampering

Long-Wire & Dipole HF Antennas

- Dipole
  - Simple and cheap
  - Hidden in attics
  - Broadband & low efficiency
  - Usually horizontally polarized
- Longwire

Magnetic Loop

- Small (<1/10 wave circumference), expensive, efficient for narrow-band, Requires careful tuning
- High immunity to nearby noise
- Somewhat directional
- Excellent for NVIS (when vertical) and skip
- Transmit varieties narrowband only and over-designed for QRP

- Needed: wideband capable, HF, “efficient”, travel, transmit magloop for QRP
  - Status: research

Hiding the Signal Below the Noise Approach #2

Idea: Random Code DSSS + enhanced WSPR beacons (LF-HF) to help coordinate p-t-p links between Alice and Bob

- Medium range using NVIS (MF-HF) or ground wave
- Long range via ionospheric skip
- Asynchronous CDMA for efficient band-sharing
- Specialized antennas for portable use (in development)
- Low-moderate cost
- Regulatory issues
- Probably **invulnerable** even to well-equipped adversaries
- Only low-speed data
- Status: planned

Steganography: Hiding below or within another Signal

- Physical forms used since ancient times
- Commercially used for watermarking content
- Simplest use LSB of noisy images or sounds
- Most breakable with COTS software
- Some forms (e.g., noiseless) may be near impossible to break from a purely technical standpoint

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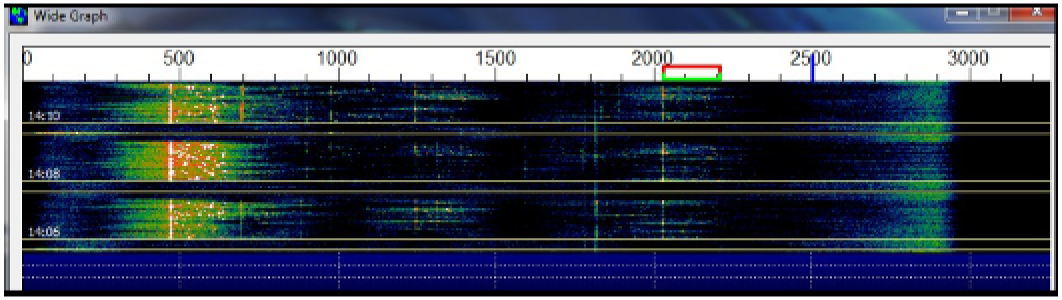
Steganographic Approach #1

Idea: Modify JT65 timing or injecting errors (e.g., in the FEC)

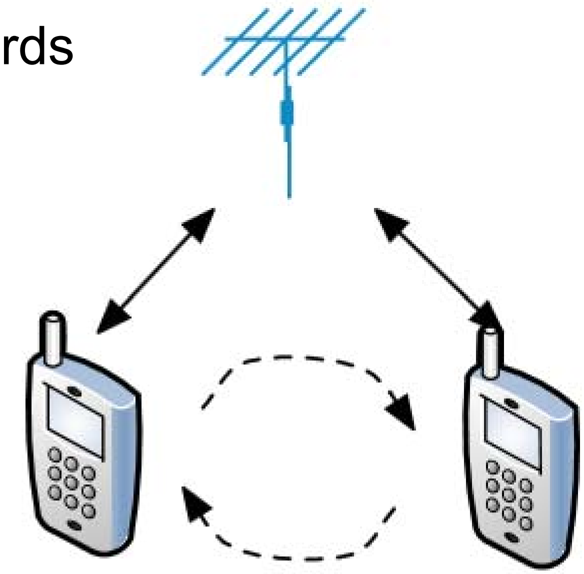


- Can, in theory, provide a long-distance capable, short message, platform
- Not tested OTA due to regulatory issues
- Probably **vulnerable** to well-equipped adversaries

Steganographic Approach #2

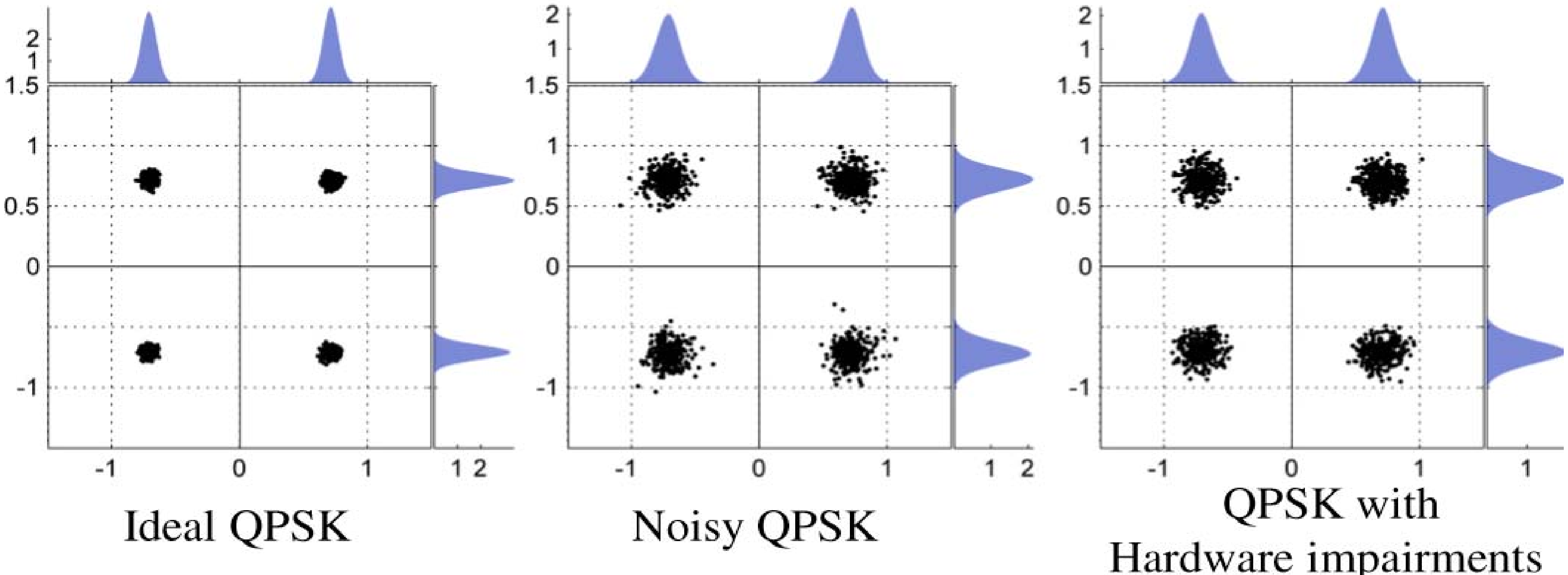
Idea: Add hidden data, as noise, to modulation constellation

- Alice and Bob send innocuous cover traffic through a router
- Mimics noisy signal or hardware impairment
- Changes fall within modulation quality standards
- Hardware/firmware assist to SDR
- Experiments conducted to verify covertness
- Hotspots and private networks



Stego Data Hidden in Noisy Constellations

- QPSK and QPSK with hardware impairments are indistinguishable, even at same SNR
- 10dB of modulation error at transmission is allowed in IEEE 802.11 standard



Key Generation

- Alice and Bob must have a way to generate shared secret key(s) in the presence of Eve
  - Should be computationally efficient
  - For DSSS it seeds the initial random spreading sequences
  - Before any communication detectable by Eve

Key Generation Method #1

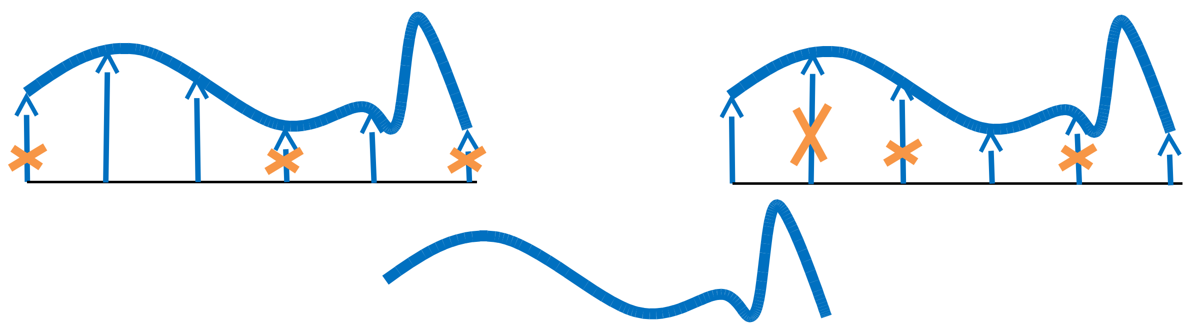
Idea: Use station “addresses” known only to Alice and Bob + randomizing factors (e.g., Time-of-Day)

- Works like RSA key dongle
- Alice's station device creates a series of random addresses
- Bob gets one, Charlie another, etc.
- Out-of-band key distribution issues
- Key generated from each address tells each party device what frequency & code to initially transmit and when to listen
- Beacons help coordinate station location and propagation

Key Generation Method #2

Idea: Exploit or create randomness at the wireless physical layer

Cooperative Jamming



- Practical key needs 2048 bits
- Exploiting existing channel randomness yields only 1-44 bps
- Selective jamming by receiver can yield >3kbps secret bits
- Receiver reconstructs signal by picking clean samples
- May work best when Alice and Bob are near (T.B.D.)

Satellites

- Commercial
  - Older C-band and newer Ku-band
    - Worldwide, 24/7, coverage
    - Easily obtained, innocuous, affordable, up- and down-link equipment
  - Almost all are “bent pipes”
    - FFT/IFFT used to clean-up up-link signals and relay on down-link
    - Signal blocking limited to narrow-band
- Military
  - FLTSAT and UFO
  - Brazilian trucker and narco exploits
- Interfering signal
  - Detection based on down-link tuned intercept receiver
  - Direction of Arrival DoA across adjacent satellites

Covert Satellite Approach #1

Idea: Random Code DSSS in C/Ku bands to enable point-to-point links between Alice and Bob

- 24/7 reliability
- Low-moderate station cost using VSAT modem + GR + HackRF/USRP
- Can use innocuous small dishes like your neighbour's
- Uncoordinated CDMA for efficient band-sharing
- Supports both voice and low-speed data
- Possibly **invulnerable** to well-equipped adversaries when (prior) DSSS covert tech is used

Covert Satellite Approach #2

Idea: Use military radar tech to narrow effective up-link beam width so only one “bird” can see it

- May prevent triangulation and reception by multiple satellites
- Might work with only small- (DTV-VSAT) moderate-size antenna
- Works with all transmitter modulation and protocols
- Inexpensive when manufactured in volume
- Similarity but simpler than Artimis pCell massive MIMO technology
- Can also be used for Line-of-Sight (LoS) and troposcatter/ducting
- Status: needs R&D

Anonymously re-purpose and existing service

Pager Networks

- Still widely used worldwide
- Simplex operation = anonymous receiver location
- Cheap and portable simple messaging
- Easily hacked
  - Assume any device ID
  - Group sharing via sub-IDs
- Encrypted messages permitted
- Anon message injection via service's email
- SDR support on Android mobiles via RTL/specialized HW

Thank you for listening...

... any questions?

Resources

- My email: wirelesswarrior@safe-mail.net
- Wireless for the Warrior http://www.wftw.nl/
- GnuRadio https://en.wikipedia.org/wiki/GNU_Radio
- HackRF http://greatscottgadgets.com/
- USRP http://www.ettus.com/
- FunCube dongle http://www.funcubedongle.com/
- Selected covert wireless tech papers: by request

More Resources

- WSJT http://physics.princeton.edu/pulsar/K1JT/wsjt.html
- QRSS http://www.w0ch.net/qrss/qrss.htm
- Future radio beacons http://www.g4jnt.com/BeaconPres-2.ppt
- Magnetic loop antennas http://www.dxzone.com/catalog/Manufacturers/Antennas/HF/Magnetic_Loop/
- Sat-jacking

  http://archive.wired.com/politics/security/news/2009/04/fleetcom
- FireChat
  - Bruce Schneier https://www.schneier.com/blog/archives/2014/10/firechat.htm
  - FC's creator http://www.wired.co.uk/news/archive/2014-06/25/firechat