Analytical Tool for Evaluating Coexistence in UL Band

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Coexistence Model Goals

- BT's Impact on 802.11b
- 802.11b's Impact on BT

Focus of Presentation

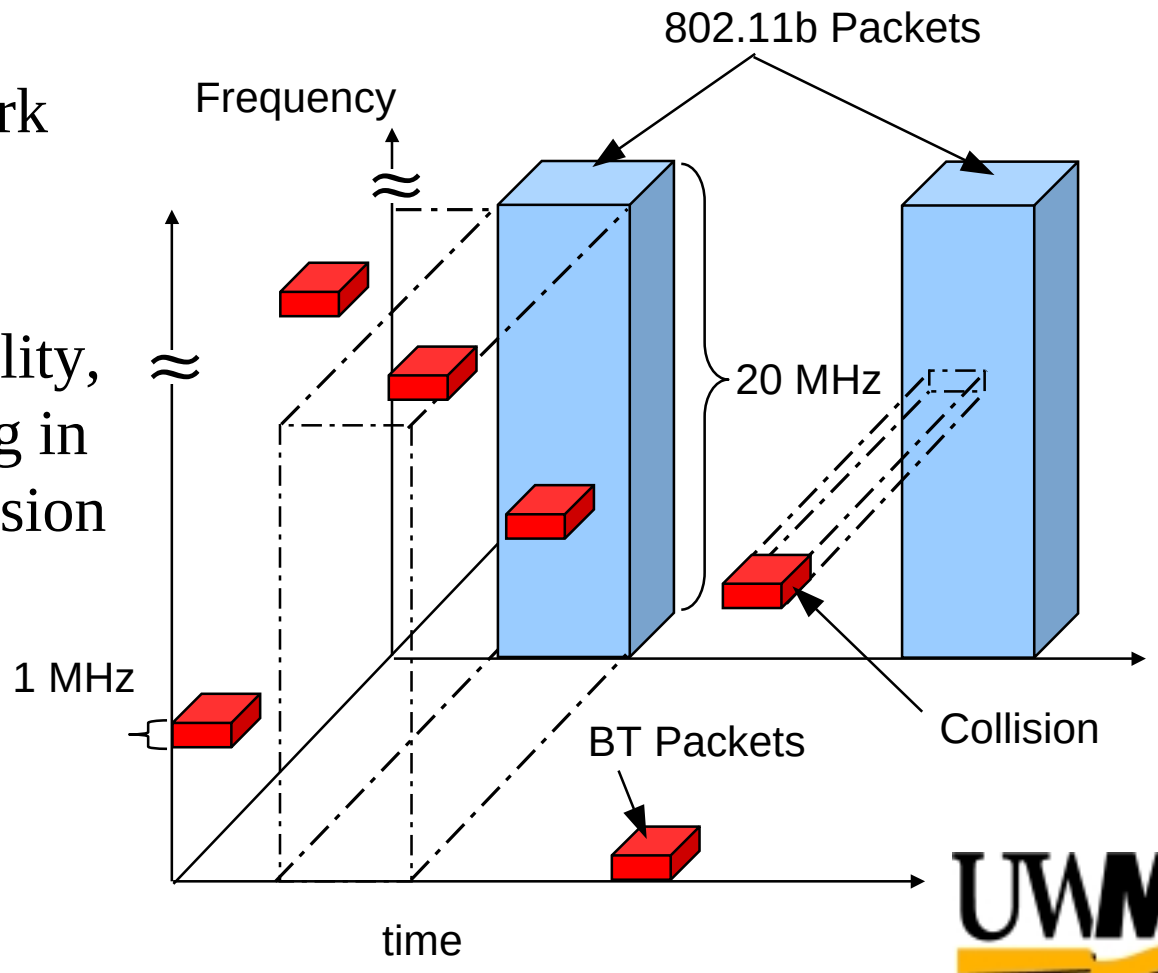
- "Arbitrary" Coexistence Scenario
- Examine Coexistence Under Specific Scenario vs. Identify Scenarios Where Coexistence is Impacted
- Empirical Study
  - Validate Model Parameters
  - Validate Coexistence Model
- General Methodology - Coexistence between WPANs & WLANs

Building on Previous Work

- G. Ennis, “Impact of Bluetooth on 802.11 direct sequence,” *IEEE P802.11-98/319*, 1998.
- J. Zyren, “Extension of Bluetooth and 802.11 direct sequence interference model,” *IEEE 802.11-98/378*, 1998.
- J. Zyren, “Reliability of IEEE 802.11 hi rate DSSS WLANs in a high density Bluetooth environment,” *Bluetooth ’99*, 1999.
- J. C. Haartsen and S. Zurbes, “Bluetooth voice and data performance in 802.11 DS WLAN environment,” *Ericsson Sig Publication*, 1999.

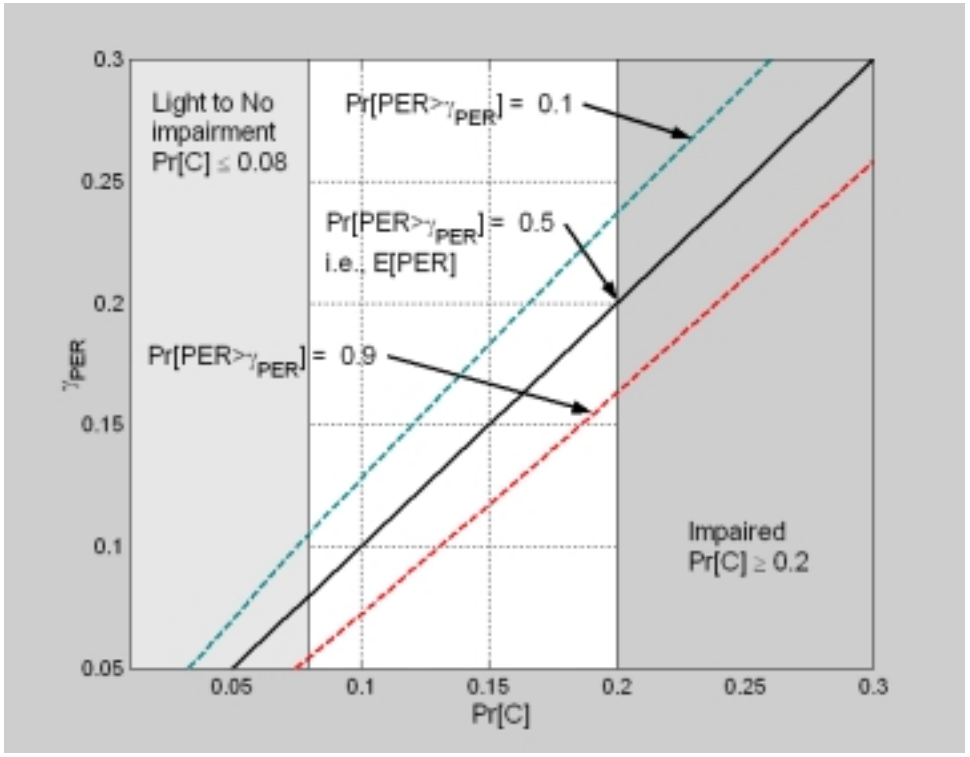
Interoperability 802.11b & BT

- Impact on Network Performance
- Pr[C] - Collision Probability, i.e, event resulting in packet retransmission
  - Time
  - Frequency
  - Relative Power



Coexistence Analysis Methodology

- Network MoPs $\Leftrightarrow \Pr[C]$
- $\Pr[C] \Leftrightarrow$ Variables
  - Stochastic Model
  - Network Parameters
    - Density
    - Activity
    - Loading
  - Radio Propagation Parameters
    - Path loss exponent
    - Shadowing
    - Desired signal T-R separation
- Evaluate - MoP w.r.t. Parameter Space



Network MOPs ⇨ Pr[C]: Packet Error Rate

- Assumption - Packet Errors IID
- Number of Errors
  - Binomial Distribution

PER Threshold

$$\Pr[PER \le N \times \gamma_{PER}] = \sum_{n=0}^{N \times \gamma_{PER}} \binom{N}{n} (\Pr[C])^n (1 - \Pr[C])^{N-n}$$

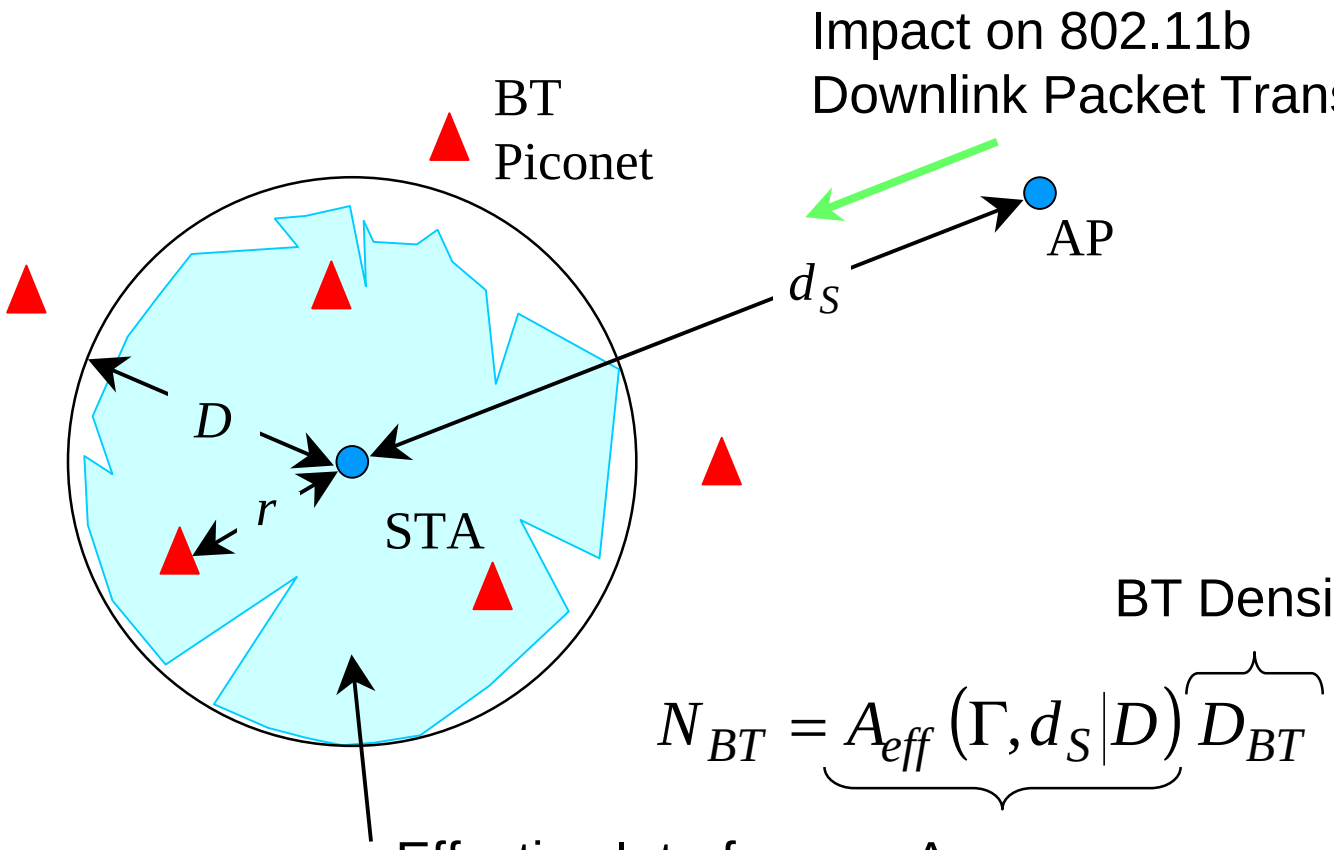
$$\cong \frac{1}{2} + \frac{1}{2} erf\left(\frac{N(\gamma_{PER} - \Pr[C])}{\sqrt{2\gamma_{PER} N \Pr[C](1-\Pr[C])}} \right)$$

Gaussian Approx.

- Normalized Expectation

$$E[PER] = \gamma_{PER} = \Pr[C]$$

Topology: 802.11b Impacted by BT



Effective Interference Area

- Approach Similar to Jake's
  % coverage area within cell's boundary

BT Rx Power

AP Rx Power

$$A_{eff}\left(\gamma_{I/S}, d_S \middle| D\right) = \int_0^{2\pi}\int_0^{D} \Pr\left(\Omega_I(r)/\Omega_S(d_S) > \gamma_{I/S}\right) r\,dr\,d\theta$$

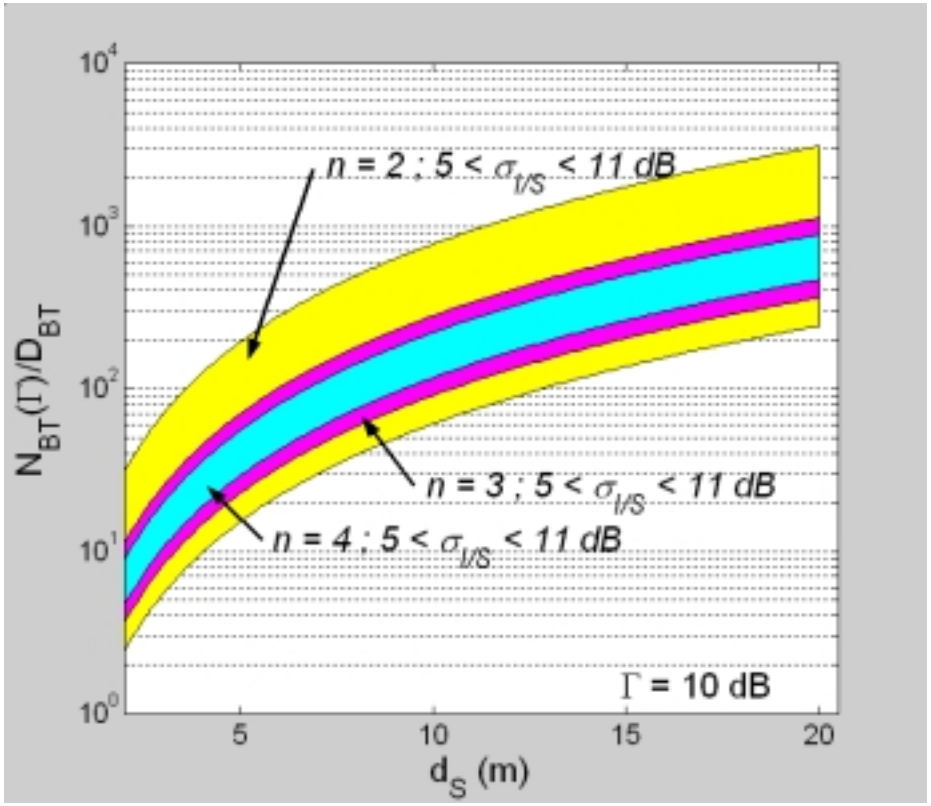
- BT node can cause interference if $\Omega_I(r)/\Omega_S(d_S) > \gamma_{I/S}$
- Let $\Gamma = \underbrace{\gamma_{I/S}}_{\text{Interference to Signal ratio}} - \underbrace{\Omega_{BT} + \Omega_{AP}}_{\text{BT \& AP Tx Powers}} = -10dB - 0dBm + 20dBm = \underbrace{10\ dB}_{\text{Typical Value}}$

Normalized Number BT Interferers

- Effective Interference Area

$$A_{eff}(\Gamma, d_S) = \lim_{D\to\infty} A_{eff}(\gamma_{I/S}|D)$$

$$= \pi (d_S)^2 \exp\left[\frac{2\left(\sigma_{I/S}^2 - 10n\Gamma\log_{10}(e)\right)}{(10n\log_{10}(e))^2}\right]$$



- Number of BT interferers

$$N_{BT}(\Gamma, d_S) = A_{eff}(\Gamma, d_S)\, D_{BT}$$

Stochastic Model - 802.11b Impacted by BT

- Independent BT Piconets

Expected # BT Interferers

BT Piconet Activity

Probability of at least one collision given *i* active piconets

$$\Pr[C] = \sum_{i=1}^{N_0} \binom{N_0}{i} (\Pr[A_{BT}])^i (1 - \Pr[A_{BT}])^{N_0 - i} \Pr[C_i]$$

- *i* Interferers Divided into Mutually Exclusive Events Based on Power

Likelihood of relative received power

$$\Pr[C_i] = \sum_{q=1}^{L} \left(1 - \left(1 - \Pr[C_1 | \hat{\Gamma}_q]\right)^i\right) \Pr[\hat{\Gamma}_q]$$

Probability of collision - given single active BT piconet & relative received power

Impact of Single BT Interferer

- Dichotomy Based on Time Coincidence

Time Coincidence Probability

Conditional based on Time & Power

$$\Pr\left[C_1 \middle| \hat{\Gamma}_q\right] = \Pr[n_\tau]\ \Pr\left[C_1 \middle| n_\tau, \hat{\Gamma}_q\right] + \Pr[n_\tau - 1]\ \Pr\left[C_1 \middle| n_\tau - 1, \hat{\Gamma}_q\right]$$

- Conditional Based on Time Frequency & Power

$$\Pr\left[C_1 \middle| n_\tau, \hat{\Gamma}_q\right] = 1 - \left(1 - L_{BT}\ \Pr\left[C_f \middle| \hat{\Gamma}_q\right]\right)^{n_\tau}$$

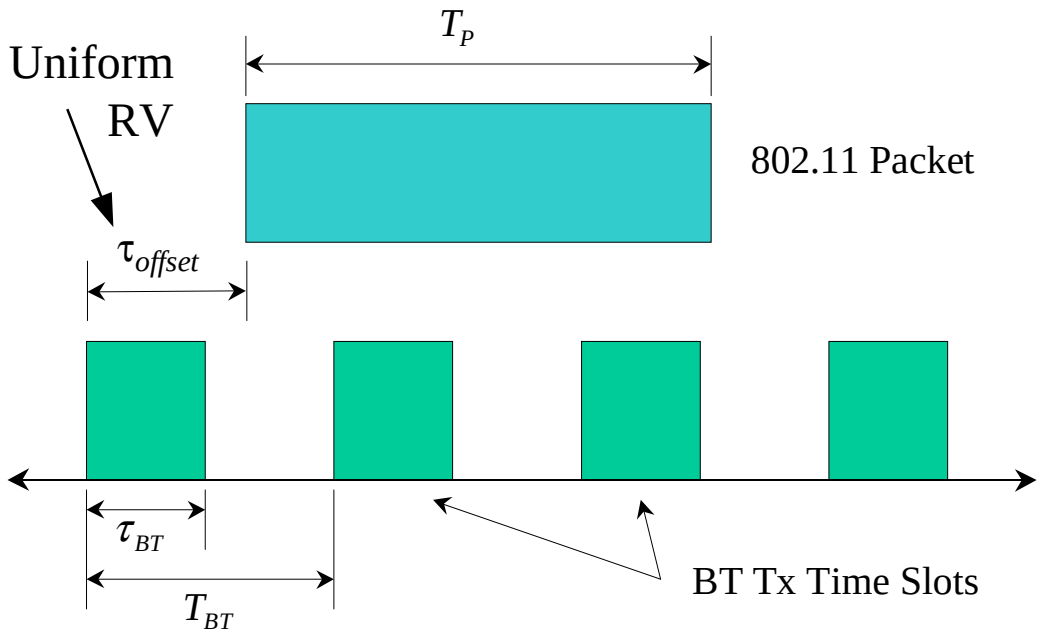
Loading factor for single BT piconet

Frequency coincidence probability given relative received power

Time Coincidence

- # BT Time Slots Coincident with 802.11b Packet

$$n_\tau = \left\lceil \frac{T_P + \tau_{BT}}{T_{BT}} \right\rceil$$



- Corresponding Probabilities

$$\Pr[n_\tau] = \frac{\tau_{BT} + T_P - (n_\tau - 1)T_{BT}}{T_{BT}}$$

$$\Pr[n_\tau - 1] = 1 - \Pr[n_\tau] \ .$$

802.11b Jamming Suppression vs. Frequency Offset

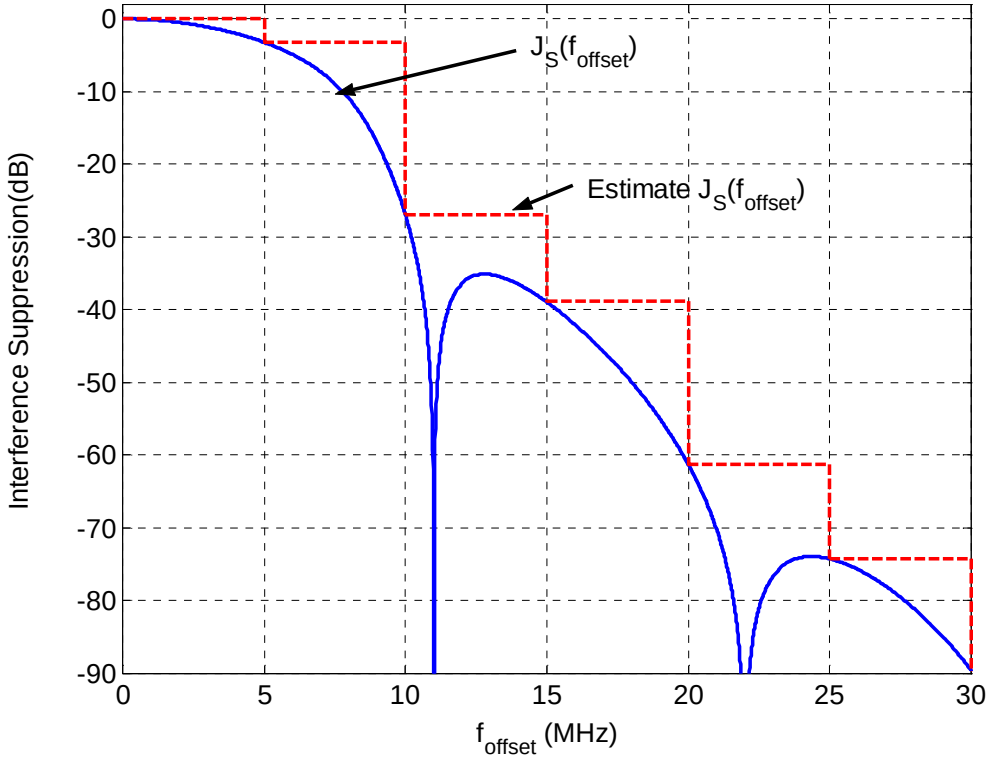
- Analytical Model - CW energy within 802.11b IF Pass Band

$$f_{offset} = \left| f_{C/BT} - f_{C/802.11b} \right|$$

$$\Gamma\left(f_{offset}\right) = \gamma_{I/S}(0) - \Omega_{BT} + \Omega_{AP} - J_S\left(f_{offset}\right)$$

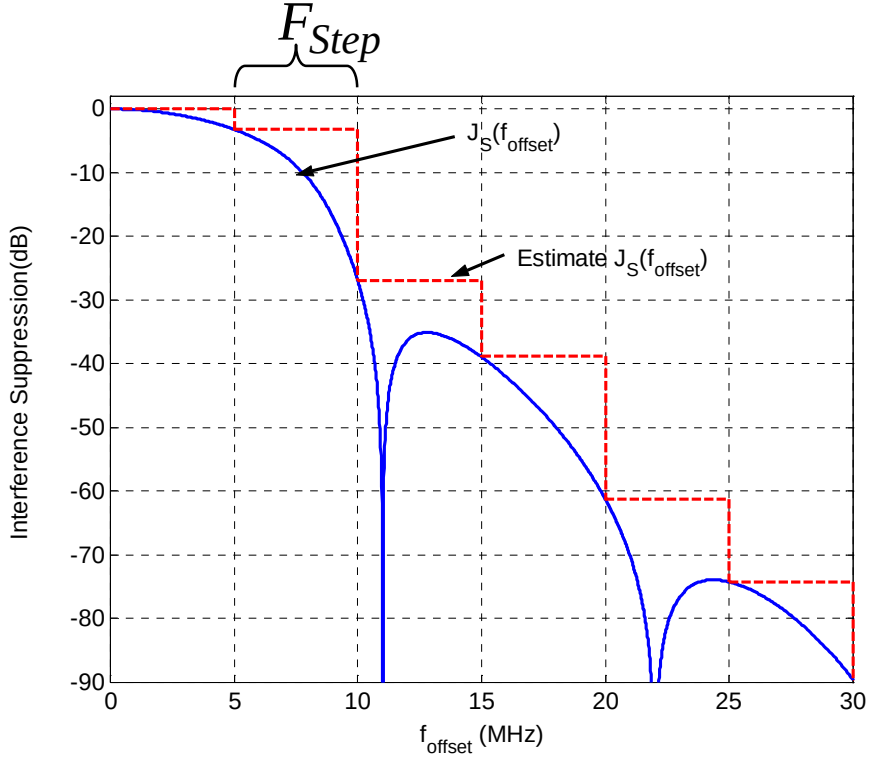
$$= -10\text{dB} - 0\text{dBm} + 20\text{dBm} - J_S\left(f_{offset}\right)$$

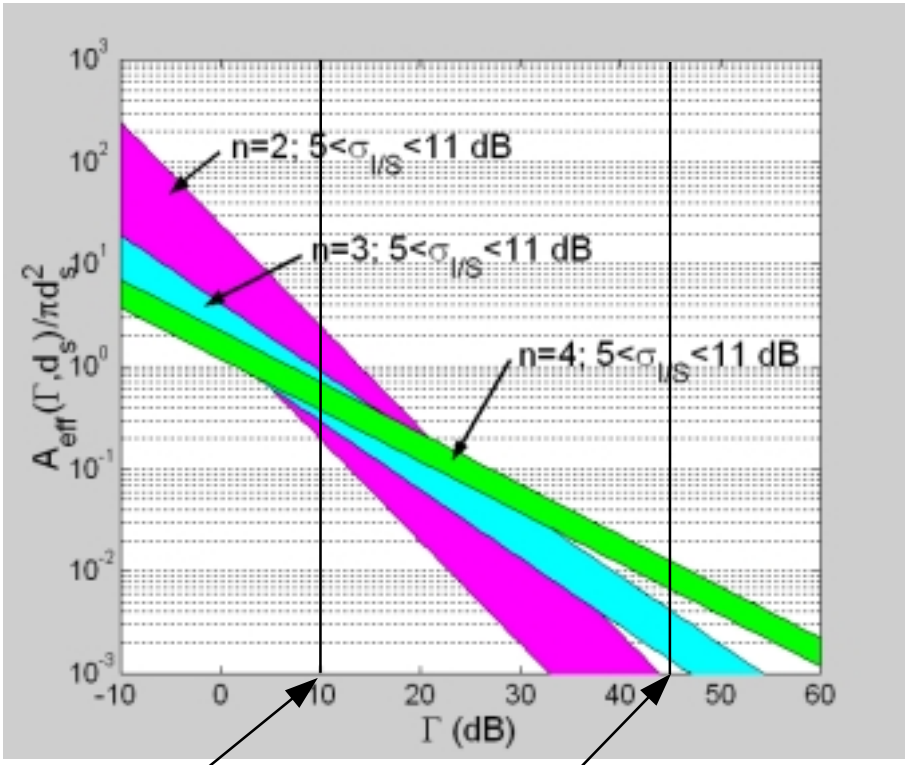
$$= 10 - J_S\left(f_{offset}\right) \text{ dB}$$



- Interference Suppression Estimate
  - Monotonic non-increasing function
  - Facilities defining mutually exclusive regions based on power

Adjacent Channel Interference





$$\Gamma(f_{offset}) = 10 - J_S(f_{offset}) \text{ dB}$$

$$\Gamma(0Hz) = 10dB$$

$$\Gamma(12.5MHz) \approx 45dB$$

Frequency Coincidence & Probabilities

- Mutually Exclusive Regions

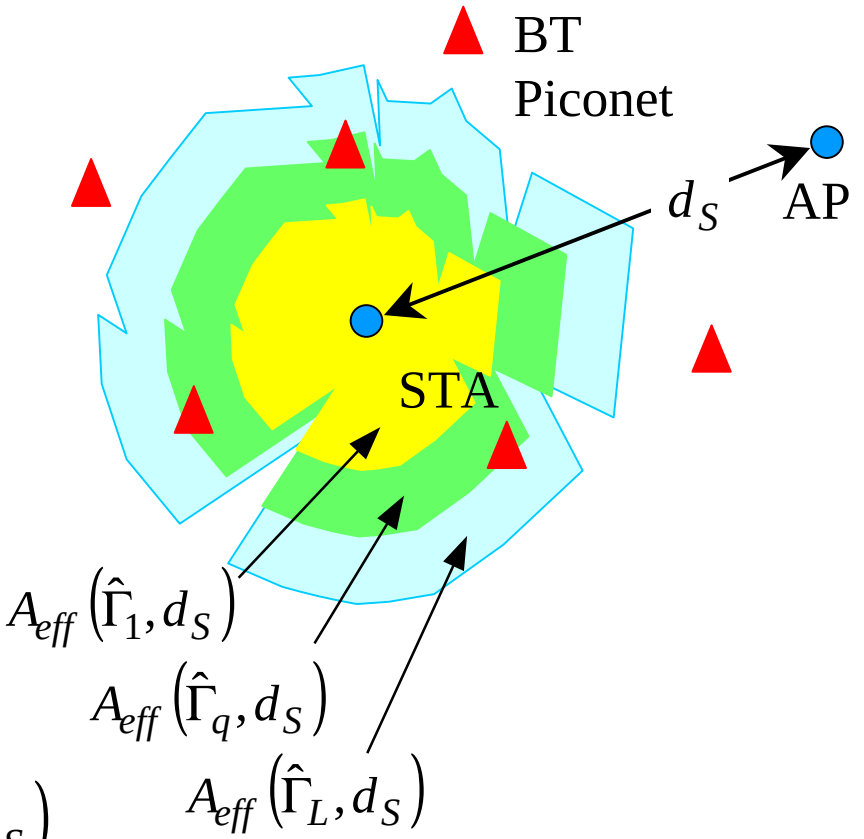
$$\hat{\Gamma}_q \equiv \hat{\Gamma}\left(f_{offset}\right)\Big|_{f_{q-1} \le f_{offset} < f_q}$$

- Corresponding Probability of Frequency Coincidence

$$\Pr\left[C_f \middle| \hat{\Gamma}_q\right] = \frac{2qF_{step}}{B_{UL}}$$

- Corresponding Probability for Region

$$\Pr\left[\hat{\Gamma}_q\right] = \frac{A_{eff}\left(\hat{\Gamma}_{q-1}, d_S\right) - A_{eff}\left(\hat{\Gamma}_q, d_S\right)}{A_{eff}\left(\hat{\Gamma}_0, d_S\right)}$$



Coexistence Stochastic Model - BT Impact on 802.11b

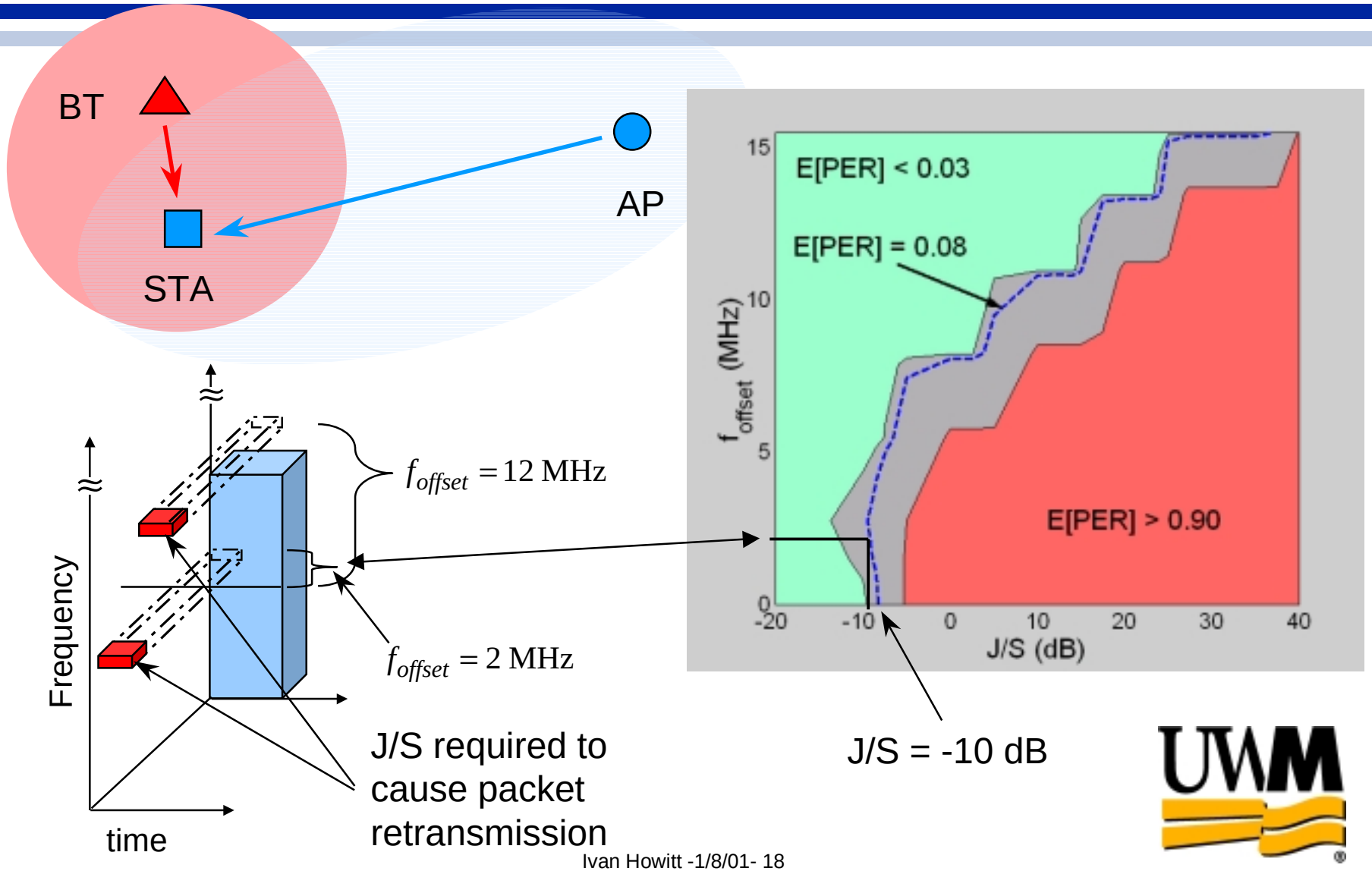
- Closed Form Solution for Pr[C]
- Six Independent Variables
  - BT Piconet Parameters
    - Piconet Loading
    - Piconet Density
    - Piconet Activity
  - Radio Propagation Parameters
    - Path loss exponent
    - Lognormal Shadowing Standard Deviation
    - 802.11b Tx to Rx Distance

Empirical Study

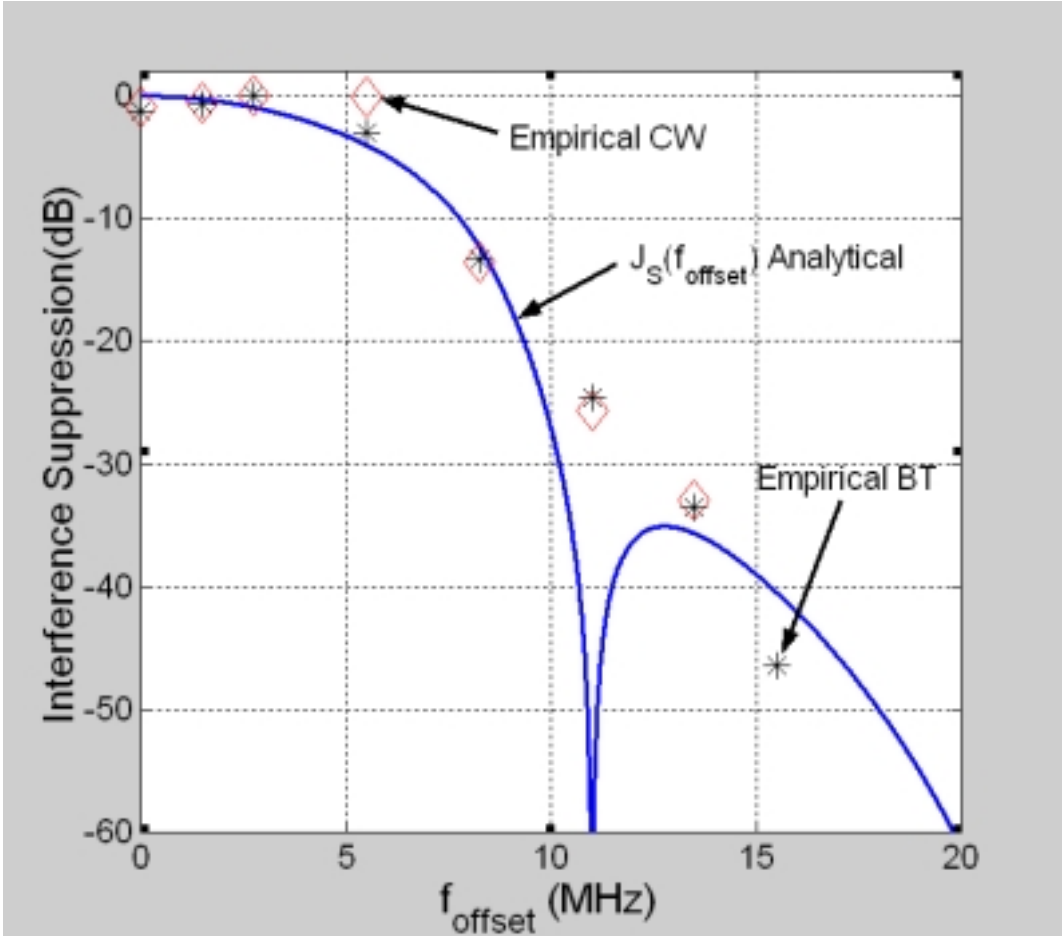
- Insight 802.11 & BT Operations
- Validate Analytical Model Assumptions
- Validate Analytical Model - Specific Scenarios

- Issue Addressed - Effect of cochannel & adjacent channel interference (BT on 802.11)

Empirical Study - BT Impact on 802.11

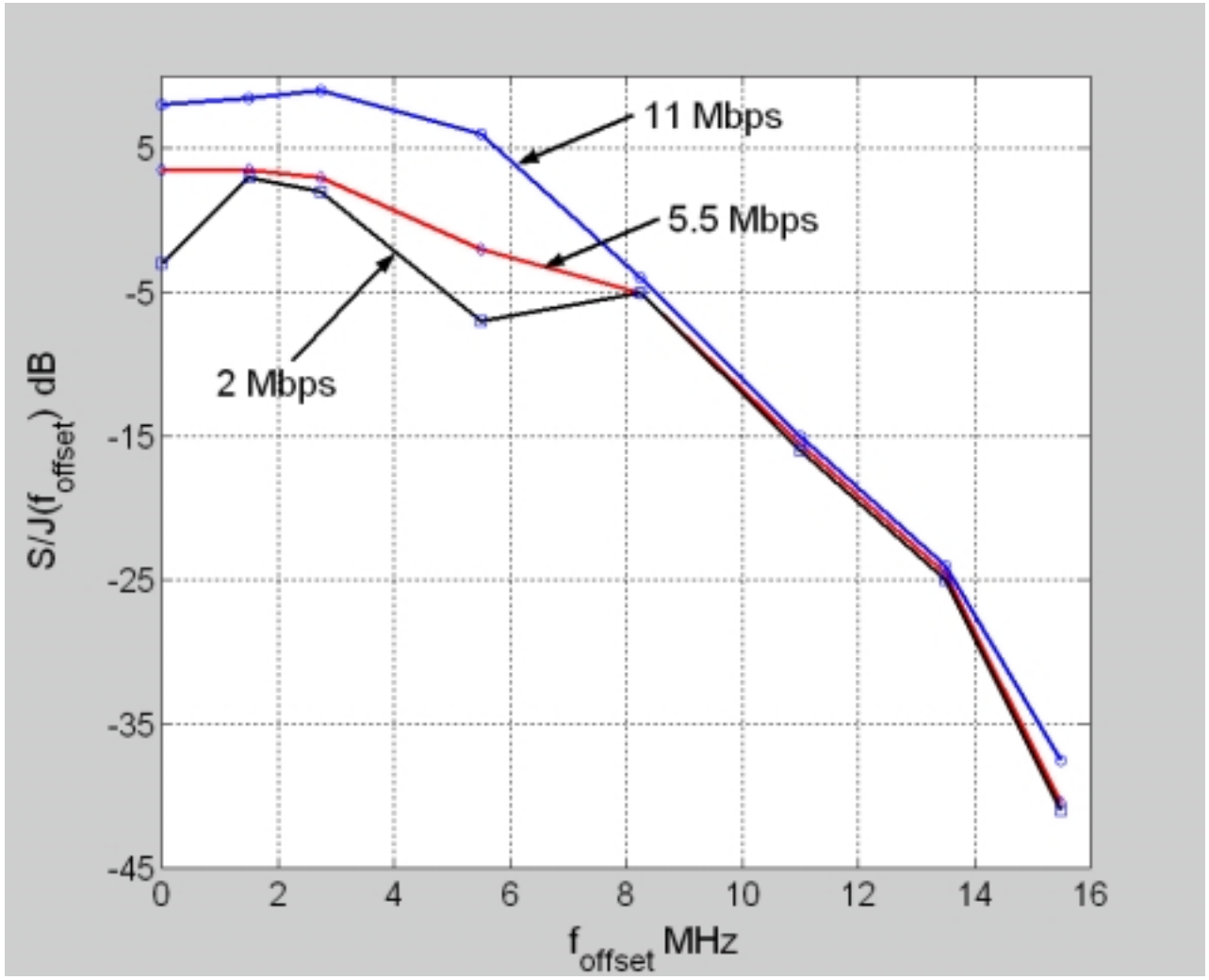


Analytical & Empirical - Jamming Suppression

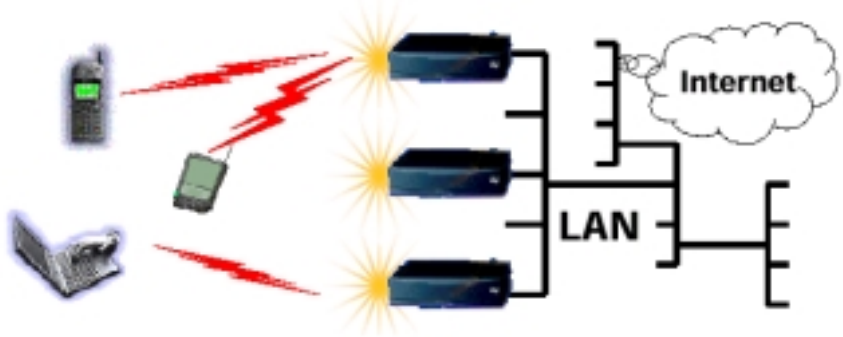


- Analytical Model
  - 802.11 DS/SS
  - CW Interference
- Empirical
  - CW Interference
  - HP - BT Signal Generator
  - Estimated expected packet error rate exceeded 8%

S/J vs. Frequency Offset & 802.11b Data Rate

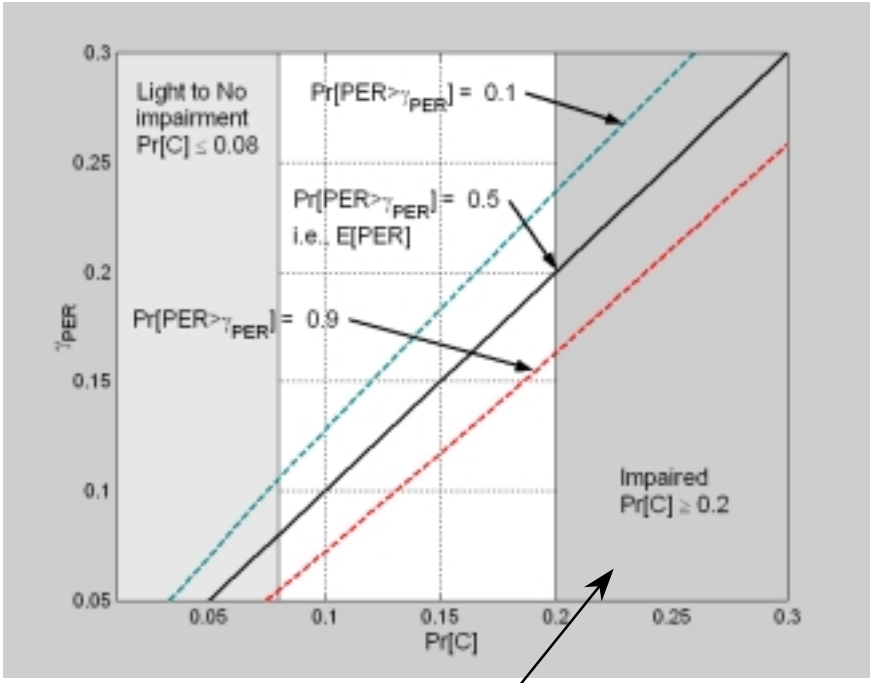


Coexistence Analysis - Office Scenario



- MOP Criteria:
  Expected PER > 20% unacceptable
- Light Scenario
  - Telephony: 10 calls/day @ 2 min/call
  - Data: 15 emails/day @ 10 kbytes/email
- Heavy Scenario
  - Telephony: 10 calls/day @ 2 min/call
  - Data: 20 Mbytes/day

Expected Packet Error Rate vs. Collision Probability



$\Pr[C] \geq 0.2$

Defining BT Network Parameters

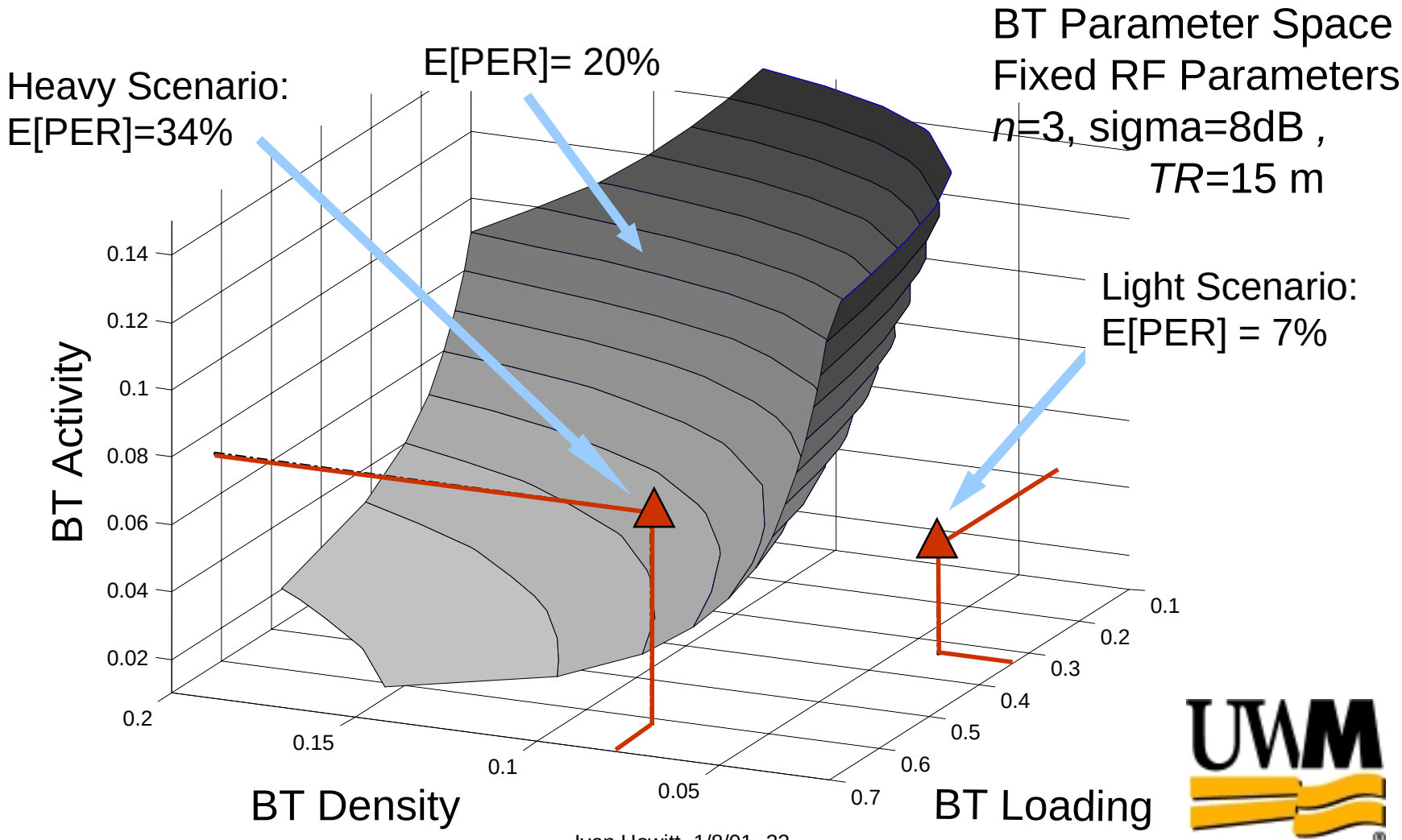
- Telephony
  - BT HV3 packet
  - Loading: 2 time slots every 6 slots, i.e., 33%
- Data Traffic
  - DH1 packet - 179 kbps throughput with 100% Loading
- Light Scenario E.g.:

$$\text{DailyActivity} = (10\times 2) + (150\times 8/179/60)\ \text{min./Day} = 20.1117$$

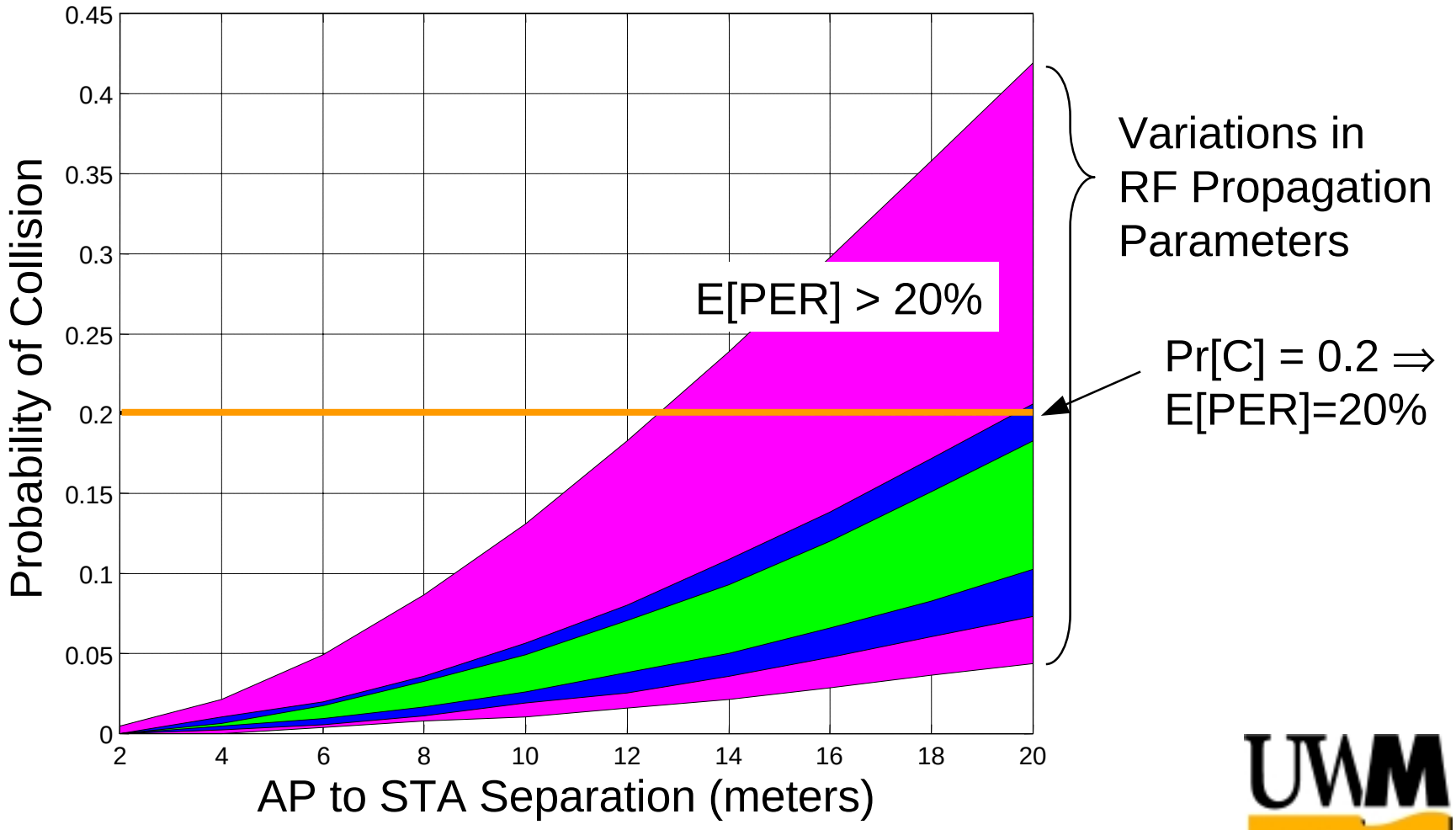
$$L_{BT} = \frac{.33(10\times 2) + 1.00(150\times 8/179/60)}{\text{DailyActivity}} = 0.3337$$

$$\Pr[A_{BT}] = \frac{\text{DailyActivity}}{8\times 60} = 0.0419$$

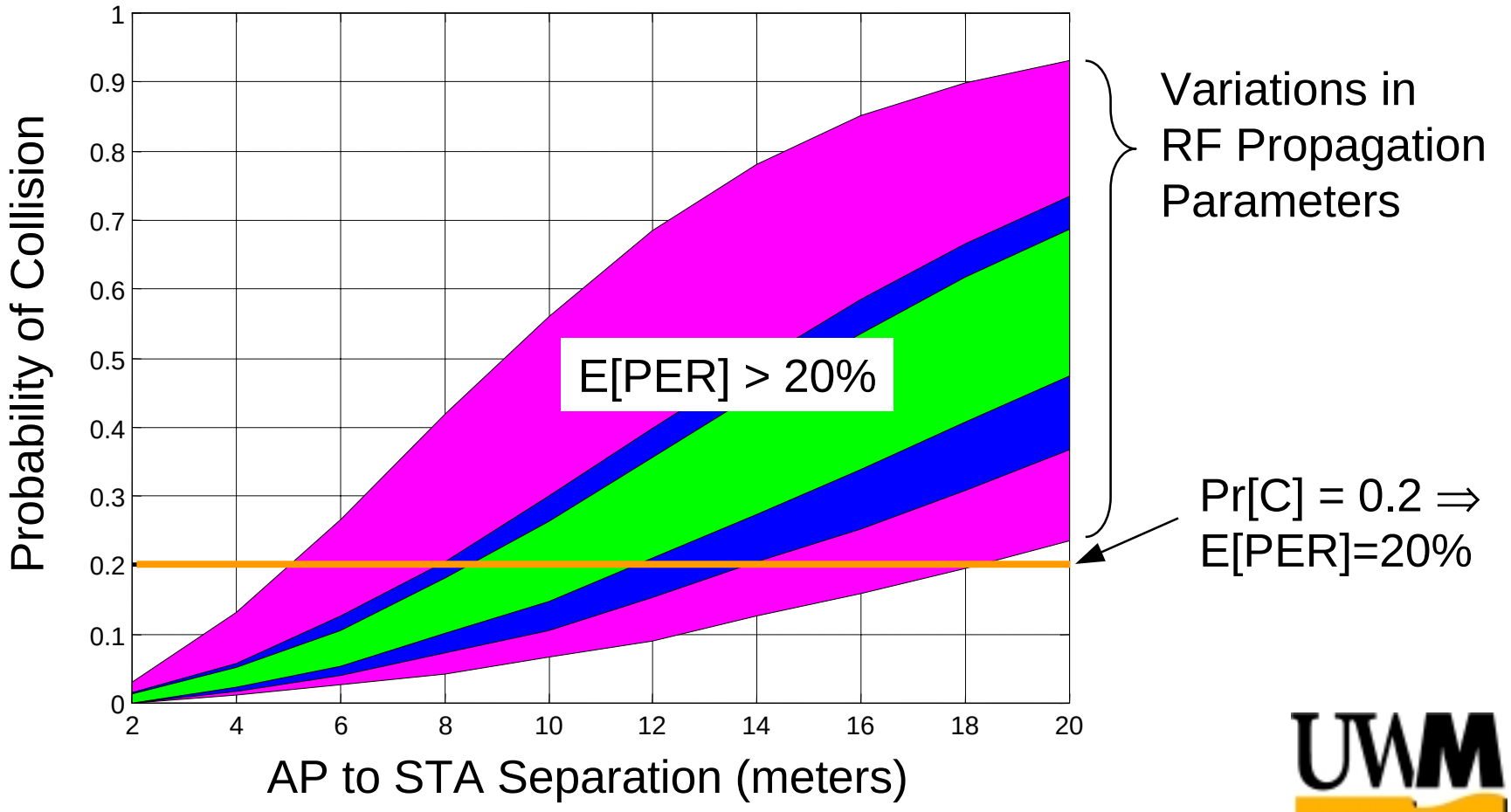
Coexistence Analysis - Office Scenario



Effect of RF Propagation
Office Scenario - Light BT



Effect of RF Propagation
Office Scenario - Heavy BT

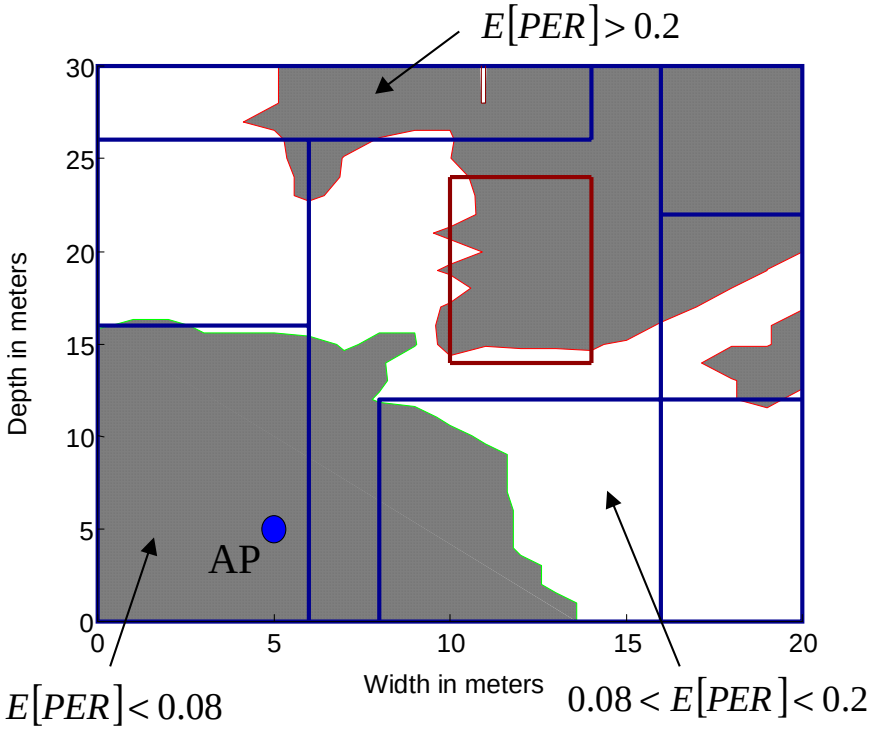


Coexistence Summary

- Network Evaluation Criteria
  - E[PER] = 8% vs. E[PER] = 20% vs. E[PER] = 40% vs. ???
  - Alternative - Evaluate Pr{E[PER] < Lower Threshold} & Pr{E[PER] > Upper Threshold} over variations in variables (see ref.)
- RF Propagation Environment
  - Significant Performance Differences with Variations of RF Parameters
  - Uncertainty in Target Environment ➡ Analysis Over Wide Range of RF Parameters for Reliable Results
- Important Criteria for Evaluating Methods for Mitigating Interference
  - Increase in Parameter Space where MOP is Satisfied

Coexistence Summary

- Method for Evaluating & Understanding Coexistence
  - Presented - Impact of BT on 802.11
  - Arbitrary
    - Communication Network
    - RF Scenario
  - Identify Scenarios Where Coexistence is Impacted
- Straight Forward Extension to Evaluate other WPANs & WLANs
- Extension - Site Specific Analysis



Additional References

- Ivan Howitt, “WLAN and WPAN Coexistence in UL Band,” In Review, Transactions on Vehicular Technology.
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- Ivan Howitt, Vinay Mitter, Jose Gutierrez, “Empirical Study for IEEE 802.11 and Bluetooth Interoperability,” VTC Spring 2001.
- Ivan Howitt, “IEEE 802.11 and Bluetooth Coexistence Analysis Methodology,” VTC Spring 2001.