Intra-Vehicle Wireless Communications: Challenges and Potential Solution

Xiao-Hong Peng

Faculty of Computing, Engineering and the Built Environment

Birmingham City University, UK.

xiahong.peng@bcu.ac.uk

BIRMINGHAM CITY University

IARIA

Keynote at InfoWare 2020

OUTLINE

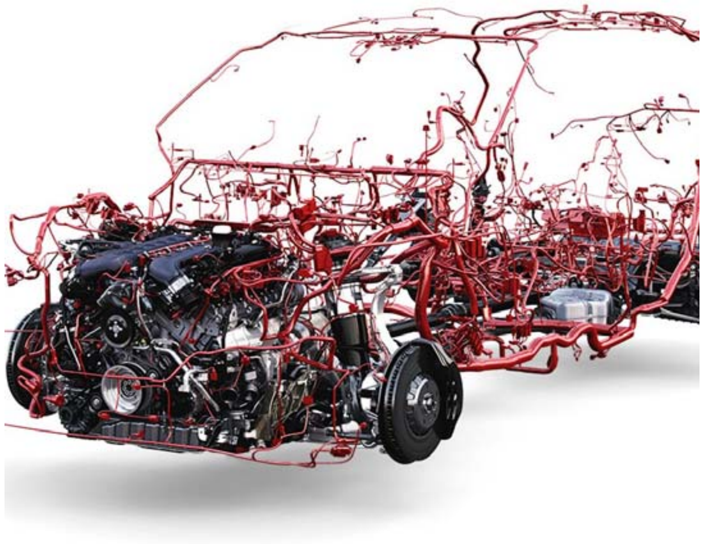
- Introduction
  - Why wireless communications in a vehicle
  - Challenges
  - Our research
- Intra-vehicle wireless channels
  - Multipath
  - Interference
  - Testbed
- Fading characteristics and loss performance
  - Power delay, RMS delay, coherence bandwidth
  - Rician k-factor
- Impacts of channel loss and electromagnetic interference on intra-vehicle wireless communications
  - EMI burst length
  - EMI gap
- Potential solution & Conclusion

BIRMINGHAM CITY University

INTRODUCTION

Why do we need wireless communications in vehicles?

- The numbers of electronic devices and sensors used in vehicles have been increased significantly over the years.
  - The number of electric control units (ECU) in a car is increased from 75 (2010) to 150 (2019).
  - Today, electronic devices are responsible for 40% of the cost of a vehicle, as compared to 18% in 2000.
- The wire connections to those devices have caused serious wire harness problems.
  - It is the third most heaviest component after the chassis and engine.
  - Can weight as much as 60 kg per car.

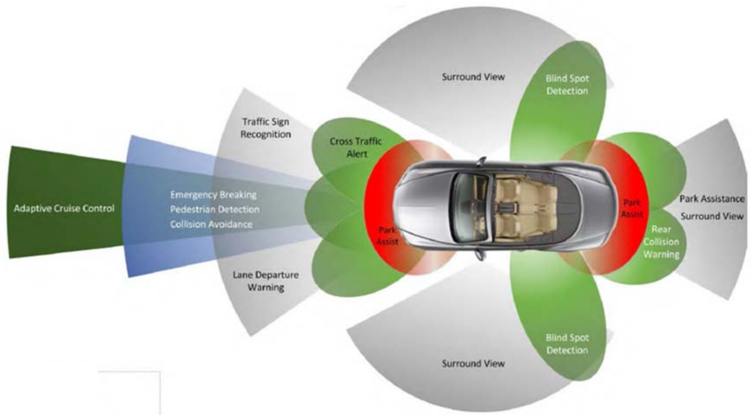


BIRMINGHAM CITY University

INTRODUCTION (CONT.)

What is the development trend of new-generation vehicles?

- New features and functionality
  - Increased number of sensors for safety
  - Autonomous driving
  - Greener



- The benefits offered by wireless solutions:
  - Save physical space
  - Reduce weight
  - Increased fuel efficiency

BIRMINGHAM CITY University

INTRODUCTION (CONT.)

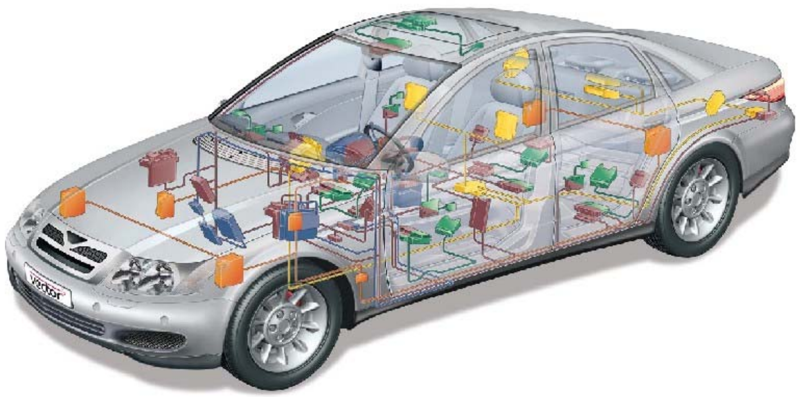
What we face and should do?

- Wireless communications currently adopted inside vehicles:
  - Bluetooth and WiFi for the infotainment system
  - GNSS for navigation
  - Tire pressure monitoring system (TPMS)

- Challenges:
  - Inherent vulnerability of wireless transmission.
  - Complex wireless channel conditions within a small enclosure.
  - Co-existence of multiple wireless signals with varied protocols.
- Our research:
  - Investigation of intra-vehicle wireless channel properties
  - Unveil data transmission performance in such a environment
  - Design of intra-vehicle wireless communications and networking protocols

BIRMINGHAM CITY University

INTRODUCTION - INTRA-VEHICLE NETWORK ARCHITECTURE



Wireless option: to reducing cabling and improve fuel efficiency

Concerns:

- Reliability
- Safety
- Scalability

Applications of Intra-Vehicle Network:

- Control of steering wheel, windows, seat positions, lighting
- Detecting road events
- Traffic monitoring
- Fuel economy and emission monitoring and control
- Driver behaviour detection
- Entertainment

BIRMINGHAM CITY University

INTRA-VEHICLE WIRELESS CHANNELS

CHANNEL CHARACTERISTICS

- Environmental conditions:
  - Electronic systems inside vehicles are much more complex than decades ago → more radiated emissions and noise sources.
  - Multipath – multiple copies of the same signal are generated in a small enclosure with various types of obstacles.
  - None-line-of-sight – transmission links between transmitters and receivers are likely to be blocked by seats, devices and passengers.

- Performance measurements:
  - Channel loss (Path loss)
  - Power profile
  - Delay profile

BIRMINGHAM CITY University

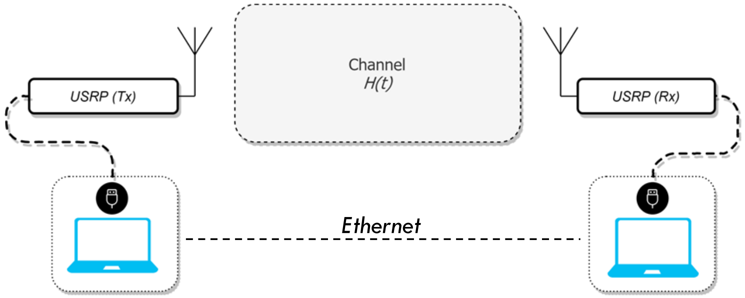
TESTBED SETUP

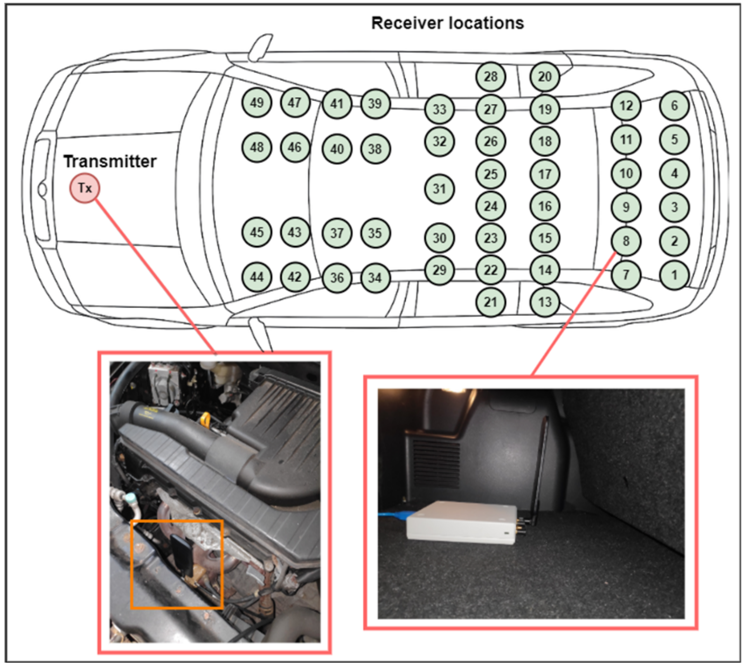
❖ Equipment and settings

- 2x Ettus USRP B210 (Software Defined Radio)
- 2x Laptop
- Omnidirectional antenna
- 2 GHz – 3 GHz
- Transmitter (Tx) power : 0 dBm

❖ Testing locations

- Engine compartment
- Passenger compartment: 49 locations





ELECTROMAGNETIC INTERFERENCE (EMI)

- Two primary CISPR standards commonly applied:
  - CISPR-25 (as a reference for our research)
  - CISPR-12

- CISPR-25
  - Guidelines for assessing electrical devices in a vehicle.
  - The standards specifying the peak, average and quasi-peak limits for different frequency bands.

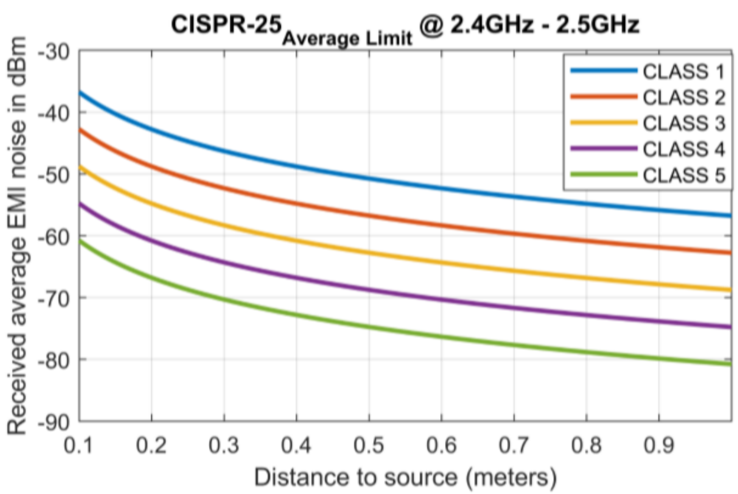
- Estimation of the detailed feature of EMI within a close proximity to EMI sources.
  - Convert the peak and average limits of the electric field strength in dBuV/m into a power level in dBm.

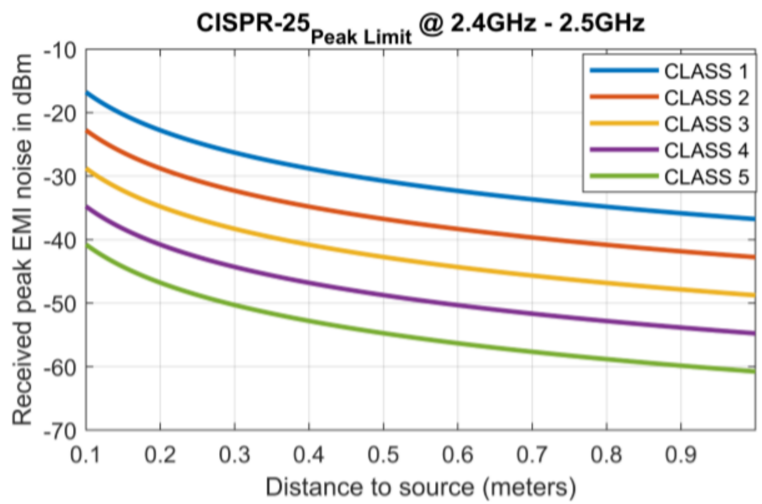
BIRMINGHAM CITY University

AVERAGE AND PEAK LIMITS

- A receiver will experience higher interference when being placed near to an EMI source.

- UWB (Ultra-Wideband) based solutions experience significant interference from EMI, compared to the narrowband-based or broadband-based solutions.

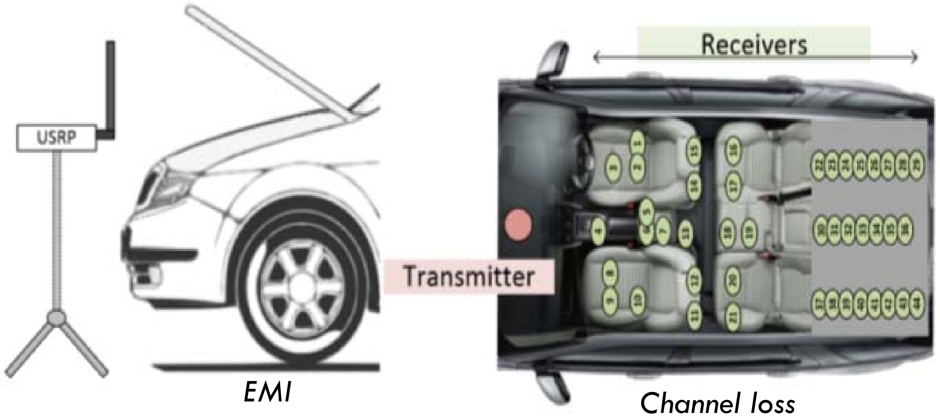




BIRMINGHAM CITY University

EXPERIMENTS

- A purpose-built testbed.
  - Channel loss
  - EMI
- Channel Loss
  - Two USRP B210
  - Omnidirectional antenna
  - Frequency: 2.4 GHz
- EMI
  - One USRP B210
  - Frequency: 2.4 GHz
  - 1 meter away from the engine compartment

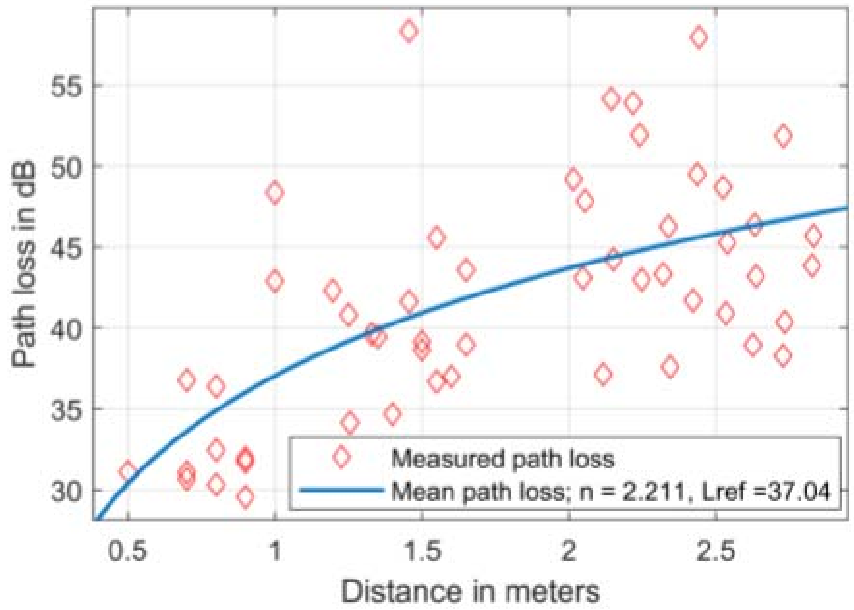


FADING CHARACTERISTICS AND LOSS PERFORMANCE

PATH LOSS

- Calculated from the measured received power.
  - Mean path loss is estimated using the Linear Regression method.
  - The loss exponent (α) extracted is close to the free space path loss. (α = 2)

- Multipath fading is the main contributor to the overall path loss.
  - The maximum fade depth or variation is measured as 18.5 dB.
  - The difference between the measured value and its local mean loss reflects fading properties.



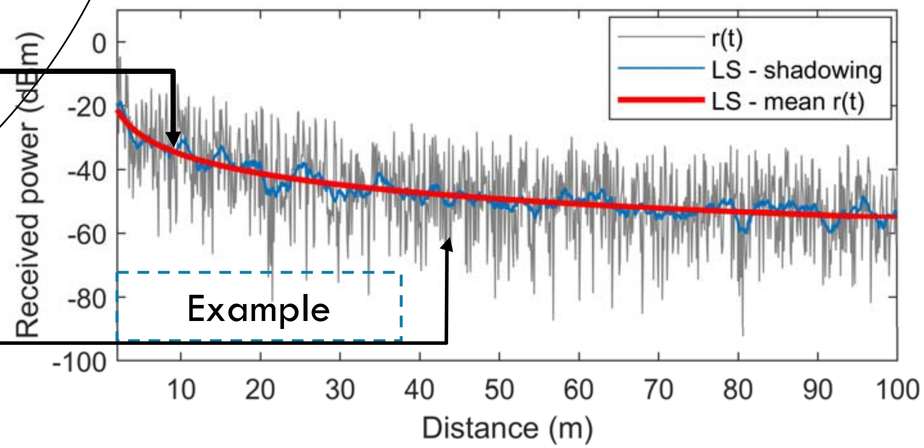
BIRMINGHAM CITY University

EXTRACTING THE LARGE-SCALE AND SMALL-SCALE FADING COMPONENTS

$$L_p = L_m + \Psi_\alpha + \beta_s$$

The power measured at different locations is further processed to extract:

- Large-scale fading (LS)
  - Slow-varying signal envelope
  - Shadowing + mean *r(t)*
- Small-scale fading
  - Fast changing received signal envelope



BIRMINGHAM CITY University

LEE ANALYTICAL METHOD

$$r(x) = \Psi_\alpha(x)\beta_s(x)$$

Small-scale fading

Large-scale fading

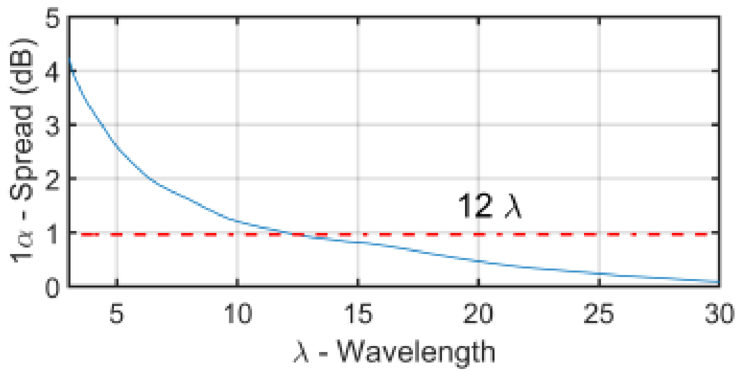
The large-scale fading is extracted by averaging the samples using an appropriately chosen averaging length *(2L)*

$$\hat{r}(x) = \frac{1}{2L}\int_{x-L}^{x+L} \Psi_\alpha(y)\beta_s(y)dy$$

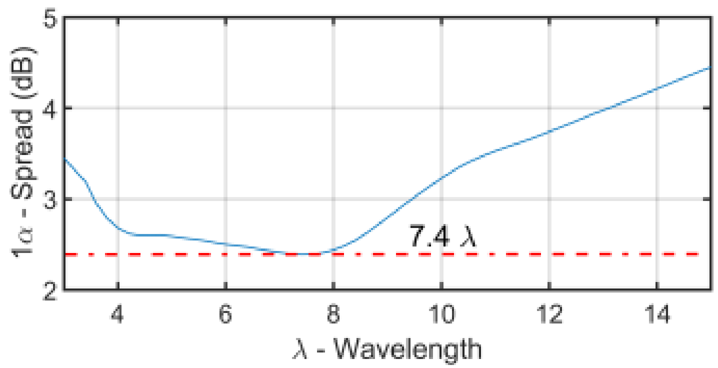
BIRMINGHAM CITY University

METHODS OF EXTRACTING FADING COMPONENTS

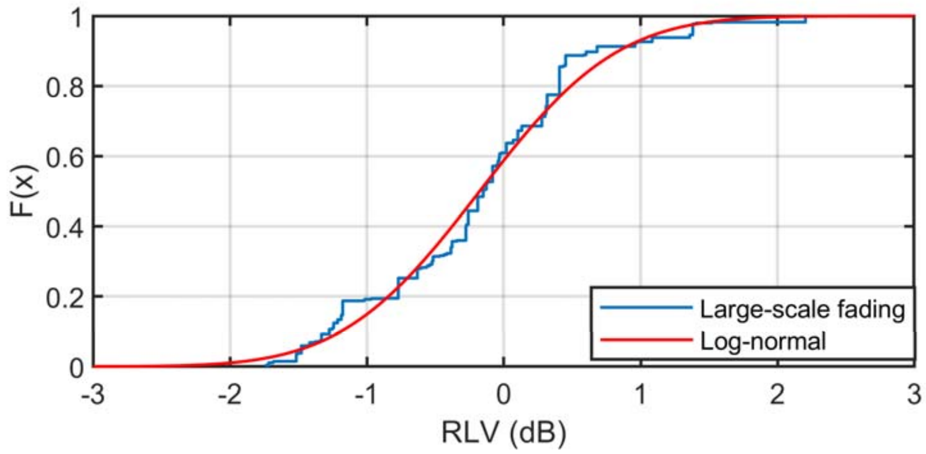
1. Lee analytical method
   - Upper bound of averaging length (2L)

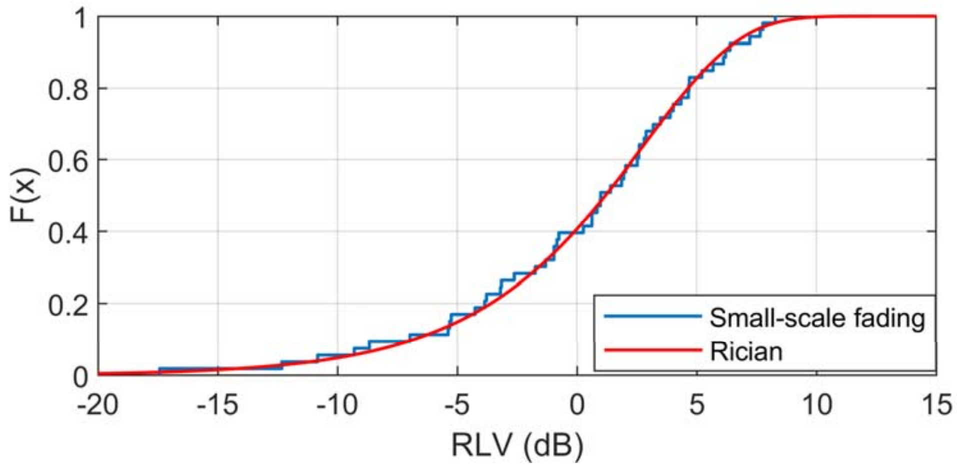


2. Generalized Lee method
   - Optimum averaging length (2L)



DISTRIBUTION OF LARGE-SCALE AND SMALL-SCALE FADING



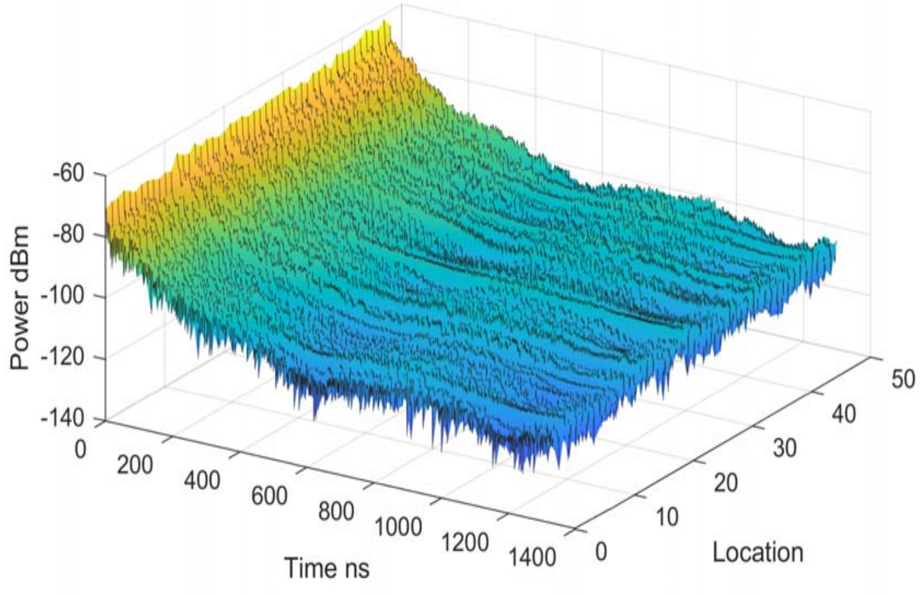


- Large-scale fading statistics.
- Small-scale fading statistics - much more dominant than large-scale fading.

BIRMINGHAM CITY University

POWER DELAY PROFILE

- The power delay profile is estimated using the inverse discrete Fourier transform (IDFT) with a Hanning window (W(f)).
- Demonstrate consistent trend across all 49 locations.
- Exponential decay with time (t).



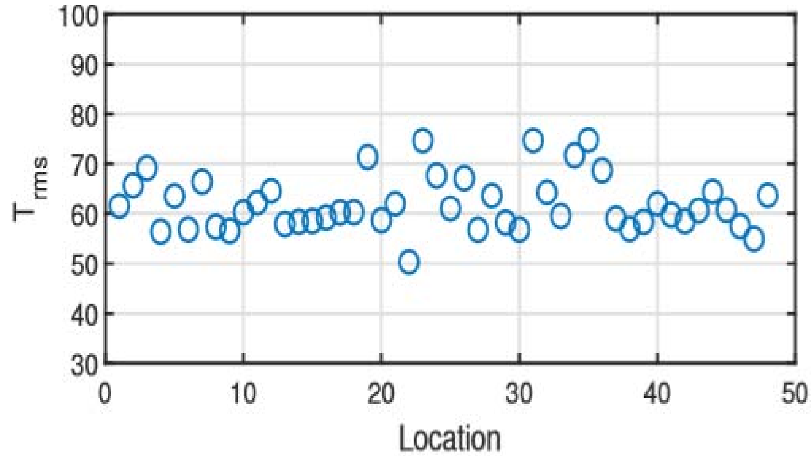
ROOT MEAN SQUARE (RMS) DELAY SPREAD

- RMS delay spread
  - The square root of the second central moment of the power delay profile

$$\sigma_\tau = \sqrt{\overline{\tau^2} - \bar{\tau}^2}$$

  - The delay spread (T_{rms}) varies between 50 –Low c 75 ns

    Average = 60.72 ns
  - Higher than the values measured in other environments (indoor, industrial, underground tunnel etc.)
- Pearson correlation test
  - Low correlation with distance (ρ = -0.02)

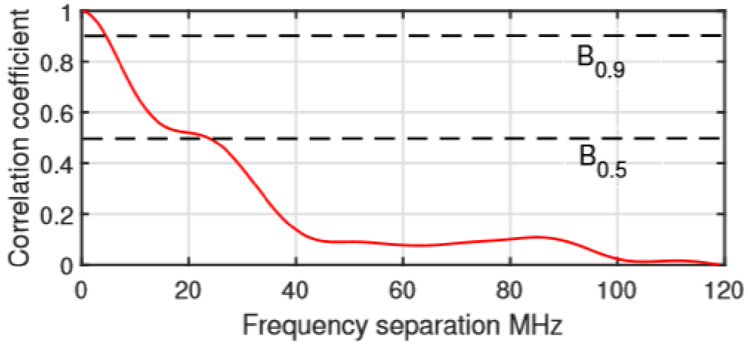


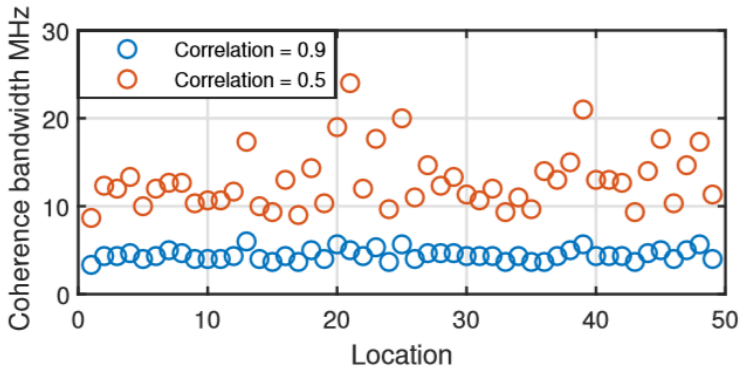
BIRMINGHAM CITY University

COHERENCE BANDWIDTH

- The coherence bandwidth was evaluated from the frequency correlation function (autocorrelation) of the frequency response of the channel.
  - Evaluated for correlation levels of 0.5 and 0.9.
  - Coherence bandwidth range: $B_{0.5}$ = 8.4 MHz – 24 MHz
  - Average = 12.95 MHz

- Pearson correlation test
  - Low correlated with distance
  - $B_{0.9}$ (ρ = -0.103) and $B_{0.5}$ (ρ = -0.194)





RICIAN K-FACTOR ANALYSIS

- The k-factor helps to decide the type of channels: Rayleigh or Rician?
  - Rician K-factor is the ratio of the dominant path to the diffuse component (multipath).

$$K = \frac{|A|^2}{\sigma^2}$$

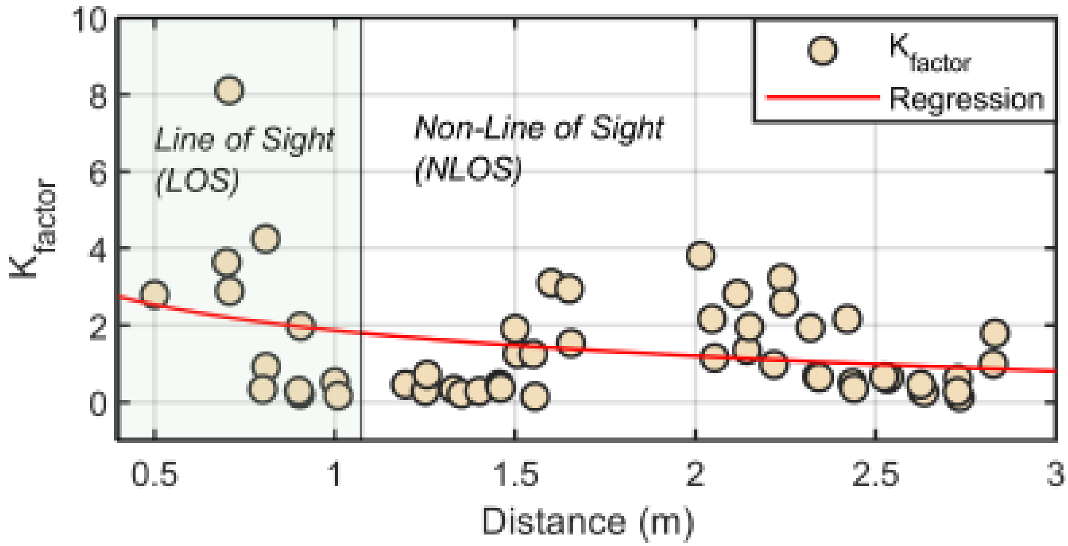
- There are various method that exist in defining or estimating Specular and Diffuse components.
  - Method of moment – does not require phase information.

BIRMINGHAM CITY University

K-FACTOR AGAINST DISTANCE

- The K-factor vary with distance with the average K-factor ≈ 0.5 (-13 dB)

- The intra-vehicle channel can be treated as a near-Rayleigh channel.



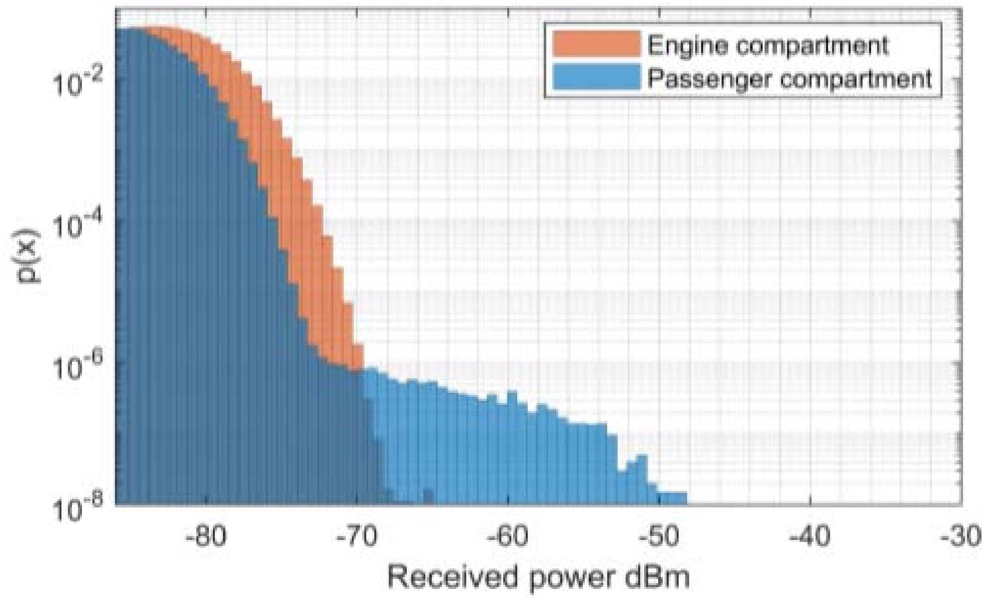
BIRMINGHAM CITY University

IMPACTS OF CHANNEL LOSS AND ELECTROMAGNETIC INTERFERENCE ON INTRA-VEHICLE WIRELESS COMMUNICATIONS

BIRMINGHAM CITY
University

EMI PROPERTY

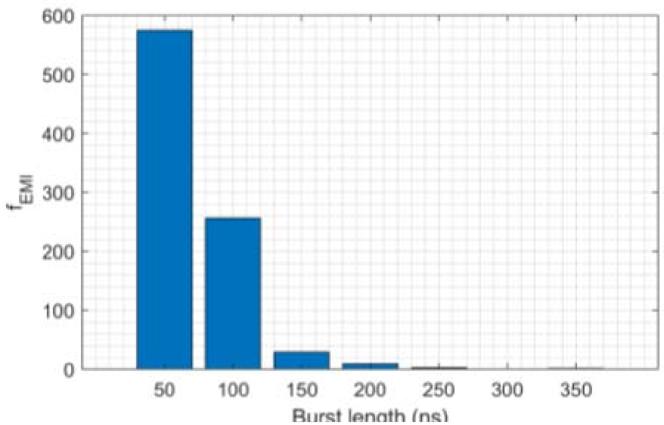
- Measured as the probability density against the time-series received power.
  - In both engine and passenger compartments
- Engine compartment
  - Peak EMI: -48.53 dBm
  - Average EMI: -62.01 dBm
- Passenger compartment
  - Peak EMI: -62.6 dBm
  - Average EMI: −88.47 dBm

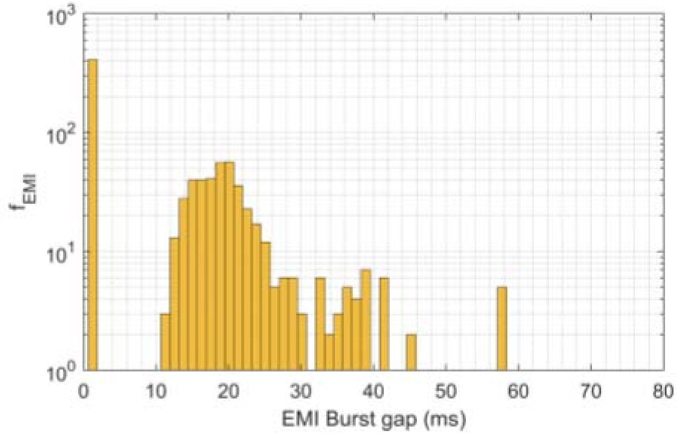


BIRMINGHAM CITY University

EMI BURST LENGTH AND GAP

- EMI burst length - the time period of the interfering signal.
- EMI burst gap - the length(gap) between two interfering signals.
- Short EMI burst (50 ns) is more likely to occur than longer burst.
- A high number of EMI bursts within a short amount of time (200 ns).



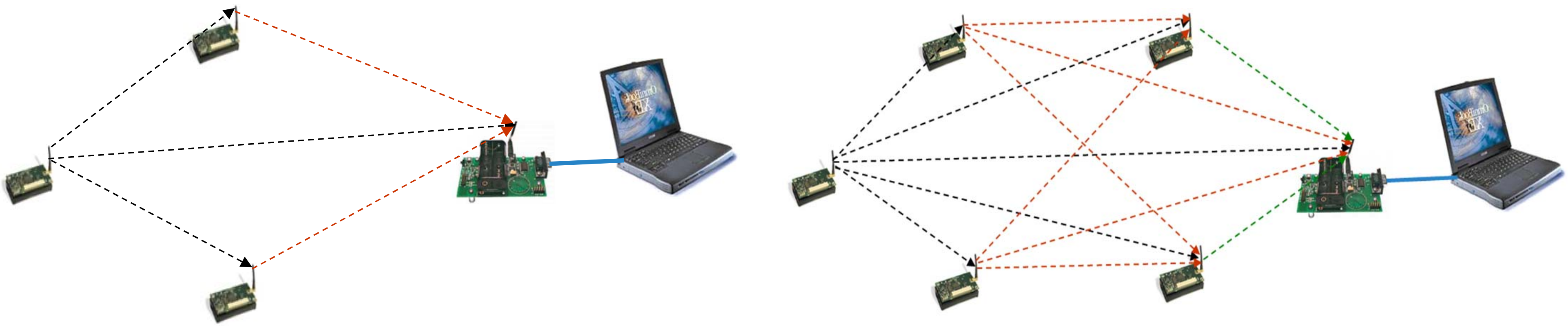


BIRMINGHAM CITY University

POTENTIAL SOLUTION

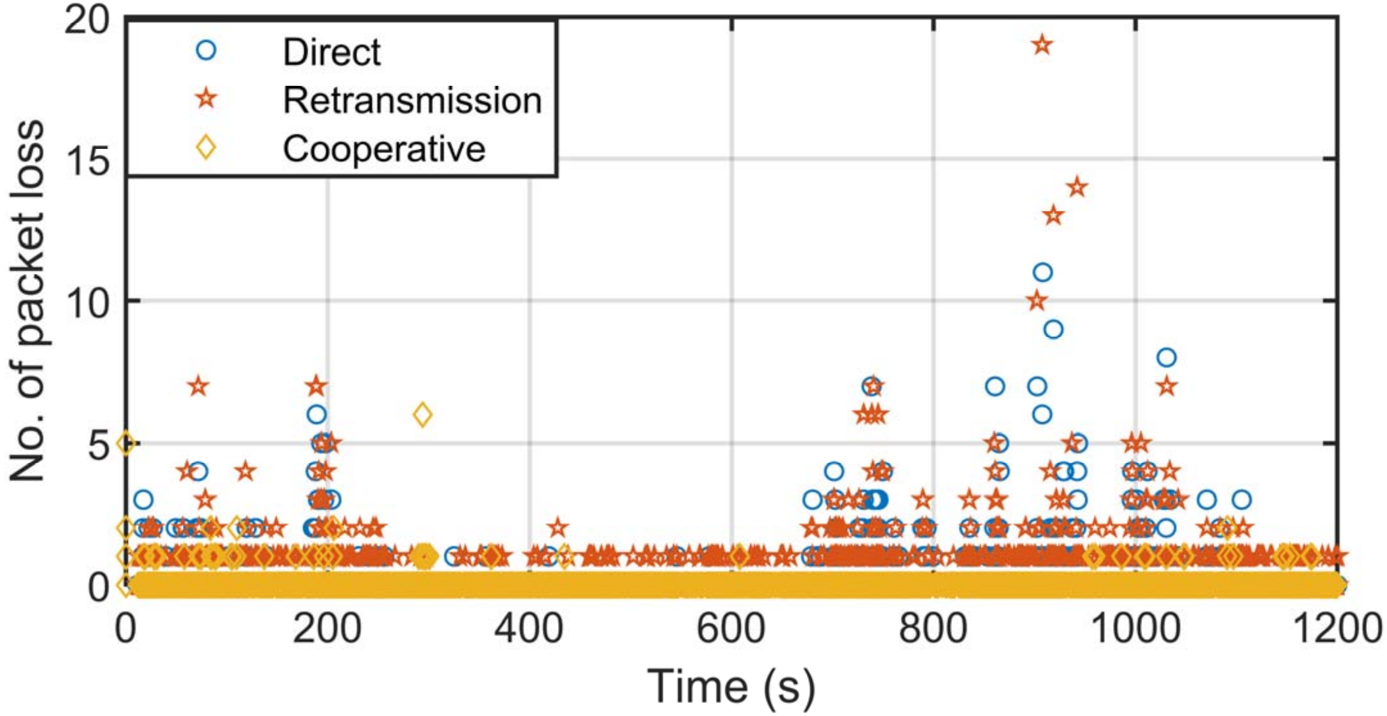
CROSS-LAYER APPROACH

COOPERATIVE RELAYING



- Creation of diversity to combat multipath fading effects.
- A spectral efficient technology with enhanced diversity and coding gains.

COOPERATIVE RELAYING PERFORMANCE – PACKET LOSS



BIRMINGHAM CITY University

PROTOCOLS AND OPTIMIZATION ALGORITHMS

- Dynamic spectrum access
- Cooperative path selection (sparse matrix)
- Data partitioning + path diversity + erasure coding → **anti cyber attack**.
- Heterogeneity settings
- Adaptive convergent algorithms for minimizing service disconnection time

BIRMINGHAM CITY University

CONCLUSION

- This is an extremely complex environment for ensuing reliable and robust wireless communications – effective and sustainable technologies in this domain are yet to be properly established and confirmed.
- Multipath fading effect is much worse than in other types of indoor environment.
- Small-scale fading is much more dominant than large-scale fading, location dependable and with more Rayleigh channel influence → high loss rates are likely.
- Key to maintaining a high level of robustness is the creation of diversity in various formats – from trading between reliability and data rate to cross-layer optimization operated in an adaptive manner.

BIRMINGHAM CITY University

THANK YOU