CAR WHISPERER: INTRA-VEHICULAR DATA BROADCASTING VIA THE AUDIO INFRASTRUCTURE

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ELECTRICAL AND COMPUTER ENGINEERING

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EXISTING TECHNOLOGIES AND PROPOSED IDEA

CABLES IN VEHICLES

Original motivation: Reduce the amount of cables within the vehicle.

Why replace cables:

- Weight – the modern wiring harness of an automobile is the second heaviest component in a vehicle behind the body
- Length – an ordinary automobile contains about 5 miles of wiring
- Maintenance – maintenance of the wiring harness is costly
- Safety – potential faults
- Security – open to jamming and eavesdropping, leading to potential hacking of the system

EXISTING EFFORTS TOWARD REMOVING CABLES

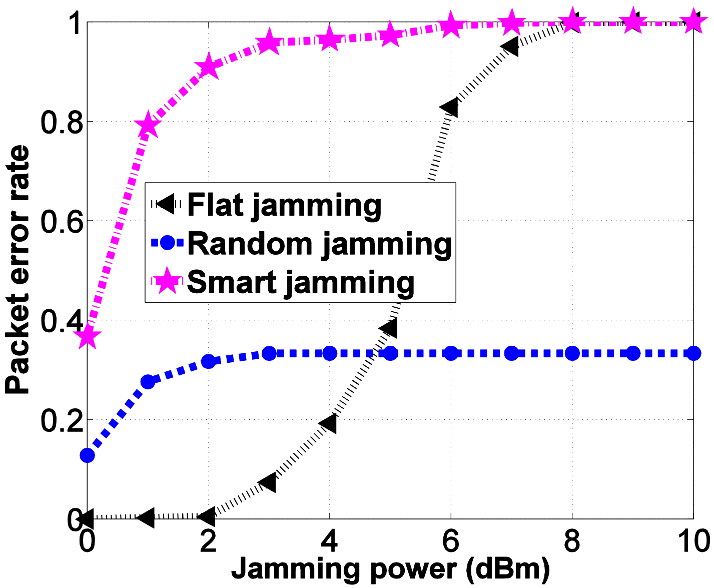
Wireless technology (for example: Bluetooth, ZigBee, Ultra Wideband (UWB), etc.)

Possible issues:

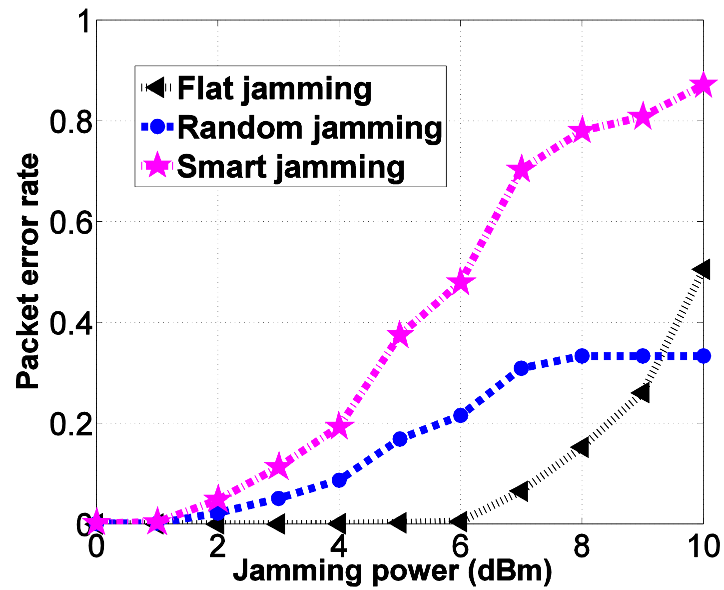
- Security – open to jamming and eavesdropping, leading to potential hacking of the system
- Interference – existing intra-vehicular communication
- Safety – potentially interfering with the operation of the vehicle

MORE ON SECURITY OF RF COMMUNICATION

a) Attacker on the moonroof



b) Attacker on the trunk door



A mobile vehicle is naturally shielded from external acoustic signals due to low-pressure fields around.

EXISTING EFFORTS TOWARD REMOVING CABLES

Vehicular Power-Line Communication (PLC)

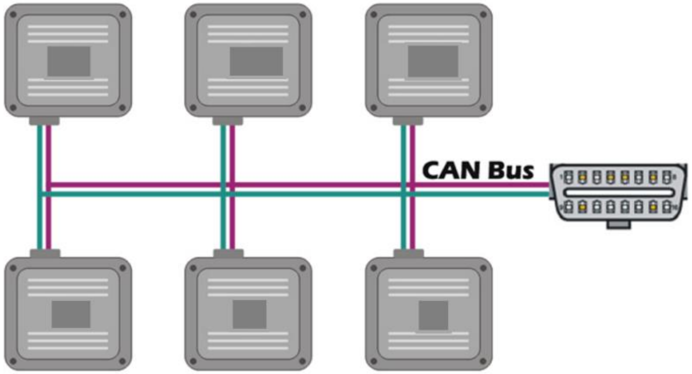
Possible issues:

- Safety – regulations on the extra load
- Channel – transmission channel is noisy and highly frequency selective due to impedance mismatch
- Security – even easier to wiretap

COMPONENTS THAT ARE CONNECTED

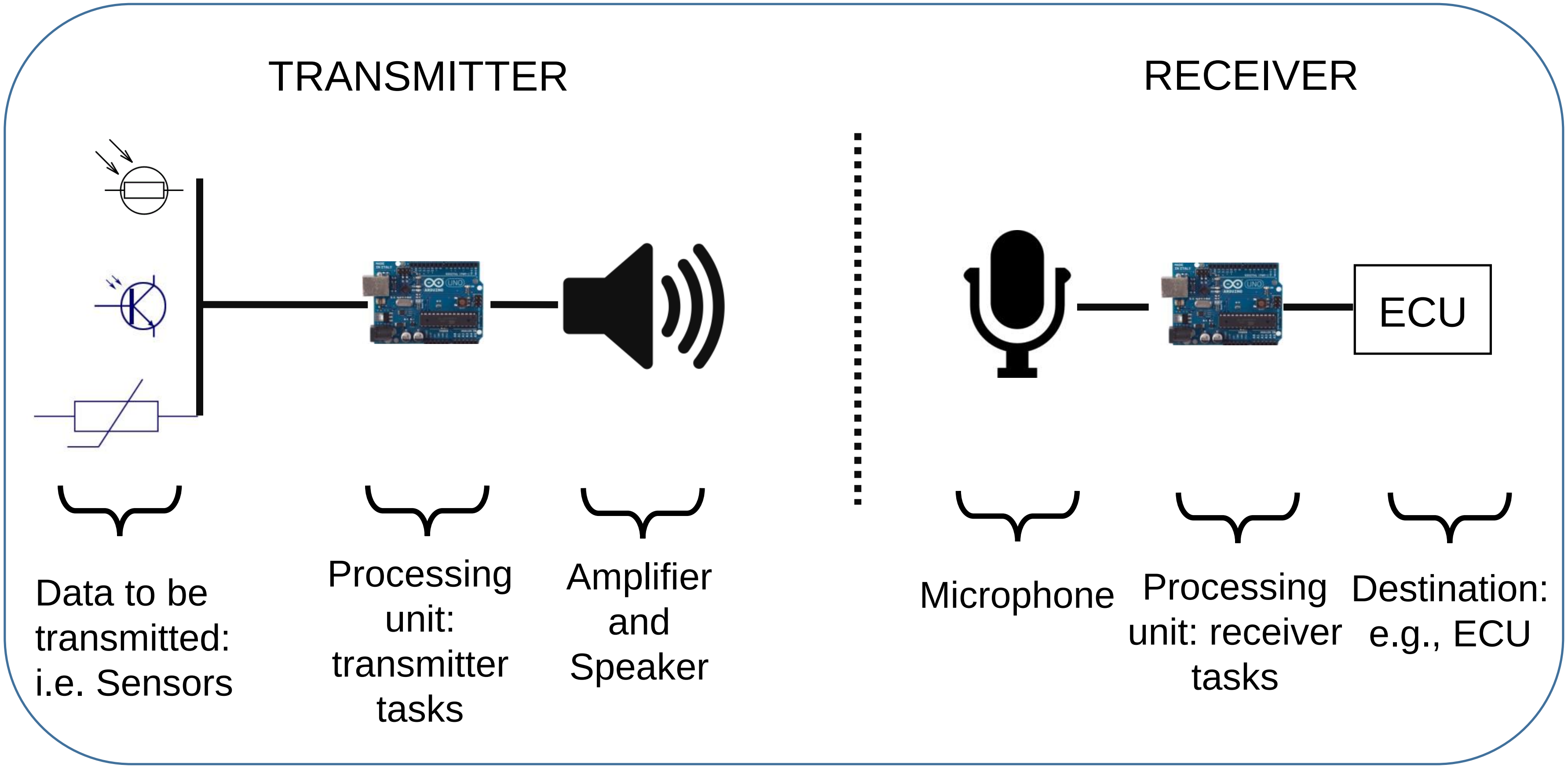
Some units/devices that are connected to the CAN system:

- Sensors of all types
- Transmission Electronic Control Unit
- Anti-Lock Braking Electronic Control Unit
- Traction Control Electronic Control Unit
- Airbag Electronic Control Unit
- Power Steering Electronic Control Unit



Many of them, such as sensors, require very low rates and intermittent connectivity

PROPOSED IDEA:
REPLACING CABLES WITH SOUND WAVES



ADVANTAGES AND DISADVANTAGES

Pros of our system:

- Existing audio infrastructure is typically high-end and it provides high-quality sound.
- Portion of non-audible frequencies are well within the dynamic range of the current speaker/mic components. Also, wideband is possible.
- Naturally secure - difficult to eavesdrop and jam by *external* attackers.
- Does not cause additional interference to the already congested wireless RF spectrum.

Cons of our system:

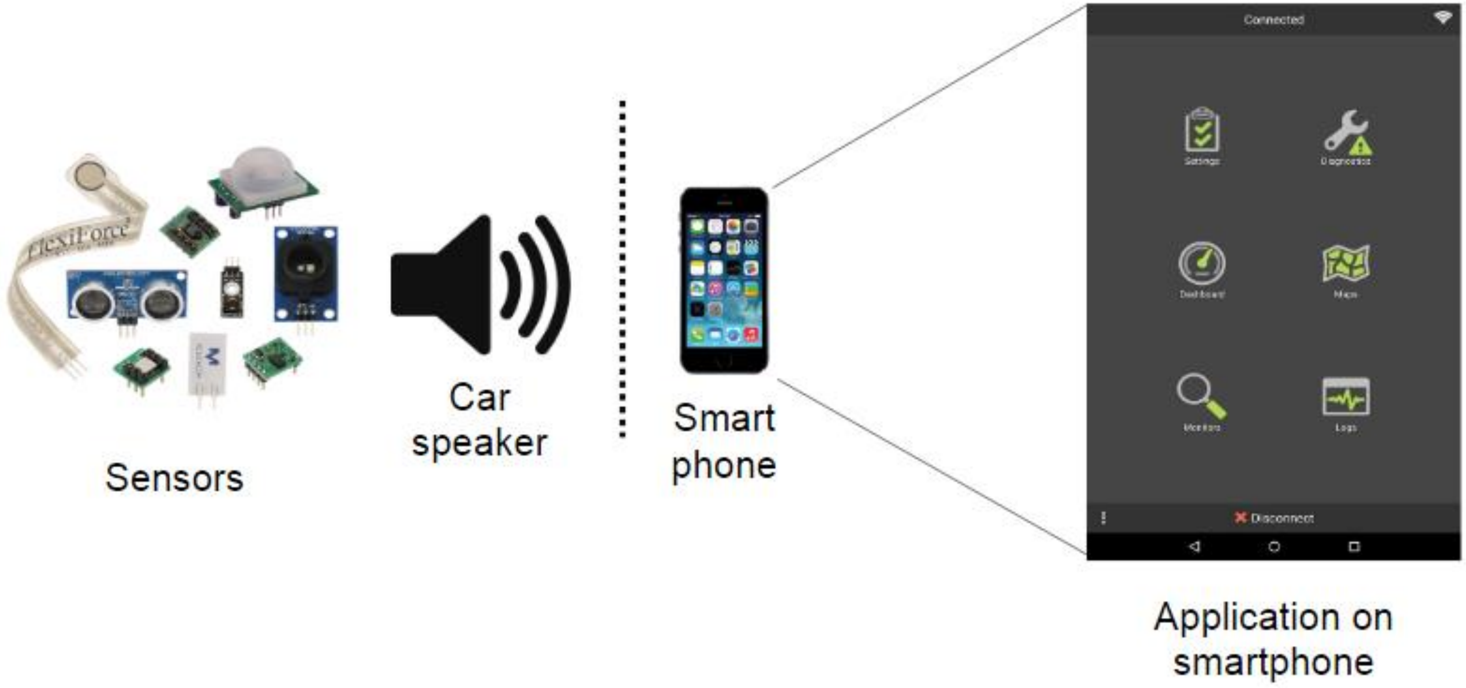
- Noise levels are highly variable and dependent on the situation (mobile, static, highway, busy roads, etc.).
- Advantage only for the components that are close to a speaker. For others, cables are required.

A POTENTIAL APPLICATION

APPLICATION OF COGNITIVE AUDIO

Car diagnostics

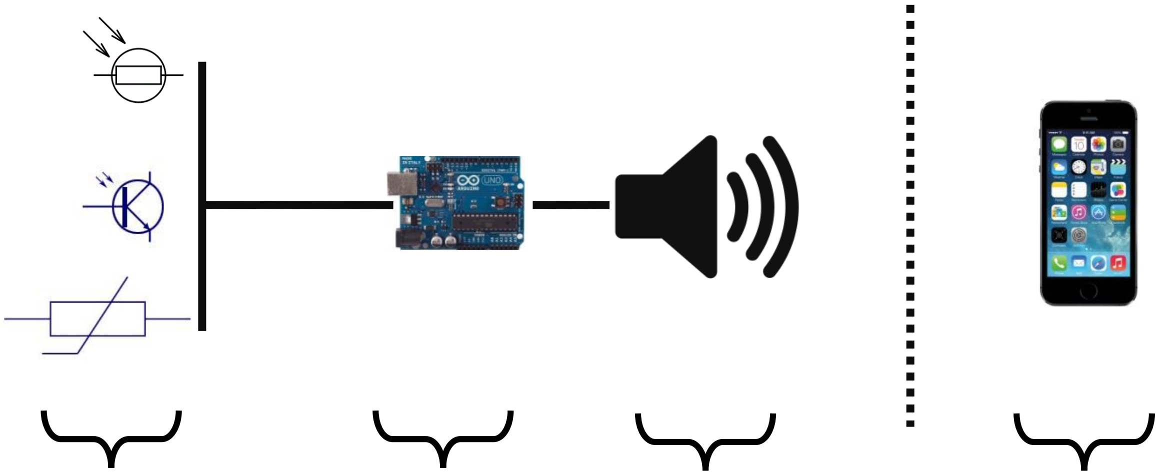
- Data from sensors contains diagnostic information.
- Encrypt data from sensors and broadcast as audio signal via speakers.
- An application on smart phone receives the data, decrypts it and gives valuable information about car's condition to user via graphs and logs.



SYSTEM

TRANSMITTER

RECEIVER



Data to be transmitted: e.g., sensors

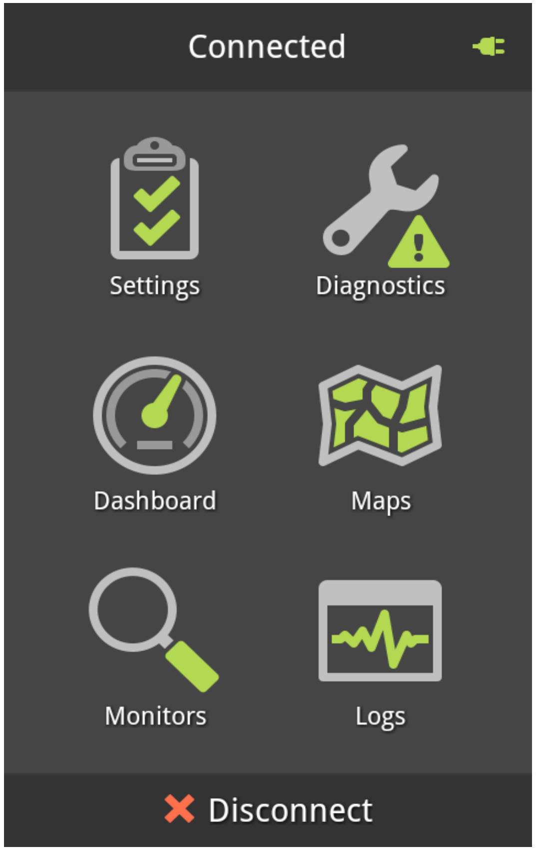
Processing unit:
- Encryption and transmission

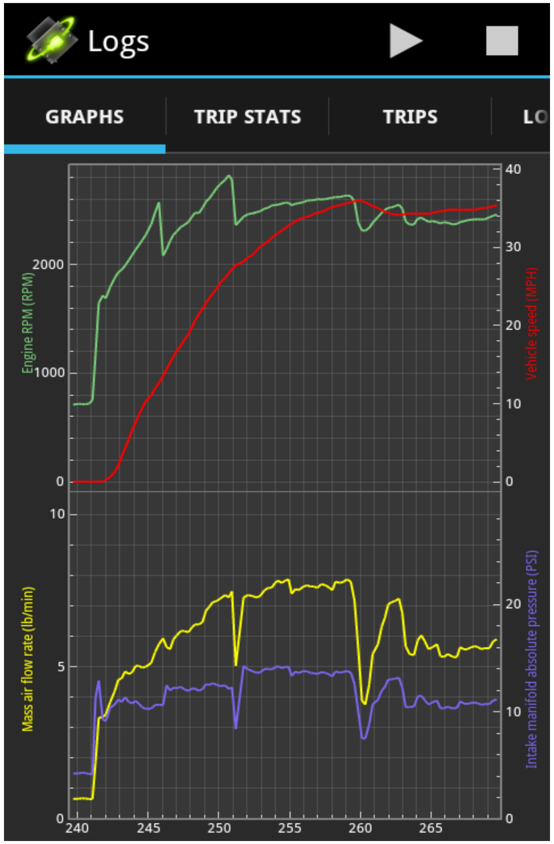
Amplifier and Speaker

Smartphone: Recording and potential decoding and decryption

SMARTPHONE APPLICATION

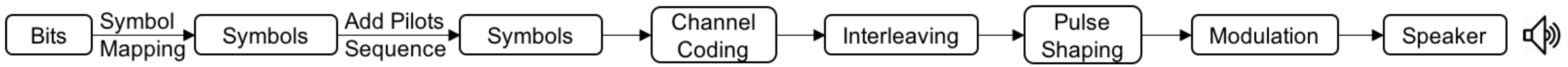
- Data received from speakers is used by smart phone to generate valuable information.



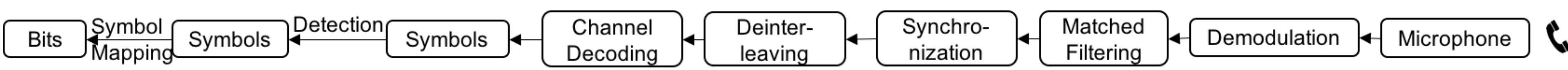


THRUST 1: COMMUNICATION

Block Diagram



Transmitter components



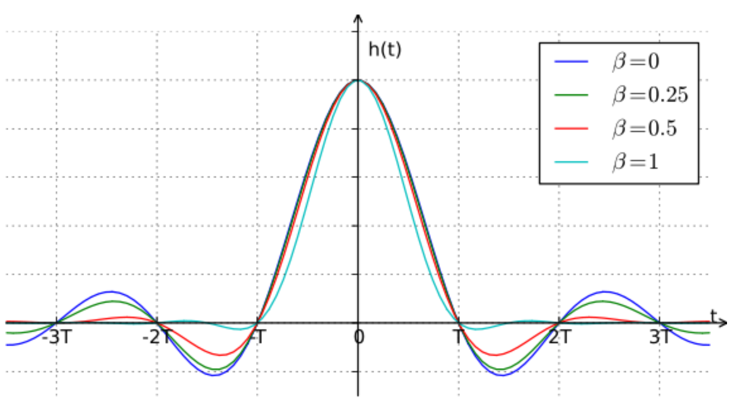
Receiver components

Pulse Shaping

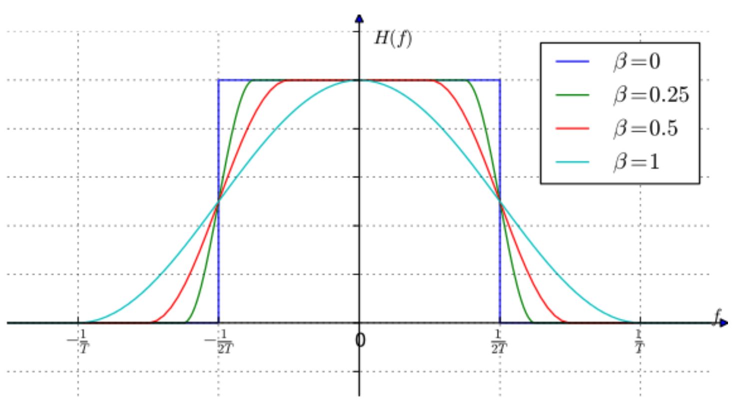
- **Implemented:** Raised cosine pulse – Nyquist pulse
- Matched filter at the receiver to prevent ISI

$$H(f)=\begin{cases} T, & |f|\leq \frac{1-\beta}{2T} \\ \frac{T}{2}\left[1+\cos\left(\frac{\pi T}{\beta}\left[|f|-\frac{1-\beta}{2T}\right]\right)\right], & \frac{1-\beta}{2T}<|f|\leq\frac{1+\beta}{2T} \\ 0, & \text{otherwise} \end{cases}$$

T, symbol period
β, roll off factor, excess bandwidth of the pulse



Time domain



Frequency domain

Synchronization, Channel Estimation, Frequency and Phase Recovery

- Typically multi-step – symbol and frame synchronization
- Uses known pilots integrated in data symbols.
- **Implemented:** Combination of symbol and frame sync at the sample level:
  - Shift the output of the matched filter (digital) at a sample level
  - Correlate with the pilot sequence over the length of the pilots
  - Choose the peak as the correct sync time – sample-level precision
  - We can control the synchronization accuracy via the sampling rate (20 μs with the current implementation)

$$\widehat{\tau}_{\text{Moose}} = \arg\max_{n} \frac{\sum_{i=K-1}^{N_p-1} \tilde{y}[n+i+N_p]\tilde{y}^*[n+i]}{\sqrt{\sum_{i=K-1}^{N_p-1} |\tilde{y}[n+i+N_p]|^2}\sqrt{\sum_{i=K-1}^{N_p-1} |\tilde{y}[n+i]|^2}}.$$

  - Frequency and phase recovery is done simultaneously following channel estimation

Channel Coding

- Linear block codes (*n*, *k*)
- **Implemented and Tested:** (7,4), (7,3), (3,1) codes

Example: (7,4) code

$$\underbrace{\begin{bmatrix} 1 & 0 & 1 & 0 \end{bmatrix}}_{k \text{ input bits}} \underbrace{\begin{bmatrix} 1 & 0 & 0 & 0 & 1 & 1 & 0 \\ 0 & 1 & 0 & 0 & 1 & 0 & 1 \\ 0 & 0 & 1 & 0 & 0 & 1 & 1 \\ 0 & 0 & 0 & 1 & 1 & 1 & 1 \end{bmatrix}}_{k \times n \text{ generator matrix}} = \underbrace{\begin{bmatrix} 1 & 0 & 1 & 0 & 1 & 0 & 1 \end{bmatrix}}_{n \text{ encoded bits}}$$

Channel Coding

- Low complexity ML decoders available.
  - Parity check
  - (7, 4) block code can correct 1 error and detect up to 2 errors in each code word
  - *y* - code word; H^T - parity check matrix; *s* - *syndrome*

$$\begin{aligned} yH^T &= cH^T + eH^T \\ &= 0 + eH^T \\ &= s \end{aligned}$$

Example:

We receive: 1000000

↓

Syndrome: 110

↓

Correction: 0000000

Error Pattern $\times H^T$	Syndrome
$[1\ 0\ 0\ 0\ 0\ 0\ 0]H^T$	$[1\ 1\ 0]$
$[0\ 1\ 0\ 0\ 0\ 0\ 0]H^T$	$[1\ 0\ 1]$
$[0\ 0\ 1\ 0\ 0\ 0\ 0]H^T$	$[0\ 1\ 1]$
$[0\ 0\ 0\ 1\ 0\ 0\ 0]H^T$	$[1\ 1\ 1]$
$[0\ 0\ 0\ 0\ 1\ 0\ 0]H^T$	$[1\ 0\ 0]$
$[0\ 0\ 0\ 0\ 0\ 1\ 0]H^T$	$[0\ 1\ 0]$
$[0\ 0\ 0\ 0\ 0\ 0\ 1]H^T$	$[0\ 0\ 1]$

Interleaving

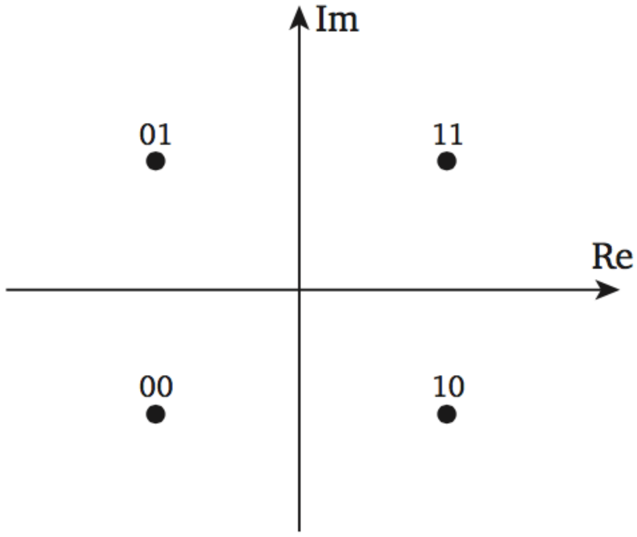
- Improve the performance of forward error correcting codes
- Avoid errors in bursts
- Rectangular interleaver

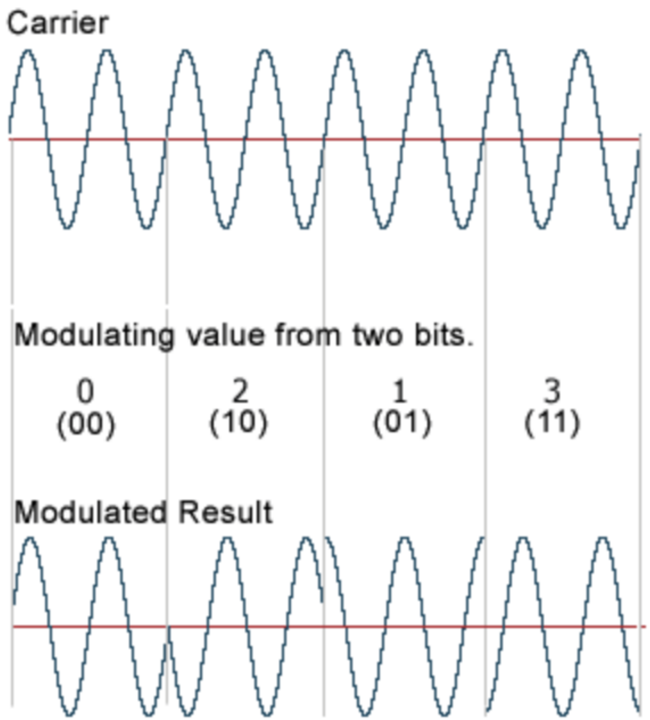
Example:

Code words:	aaaabbbbccccdddd		
Interleaver:	aaaa bbbb cccc dddd		
Interleaved:	abcdabcdabcdabcd	+ noise	abc____dabcdabcd
Deinterleaver:	abcd abcd abcd abcd		abc_ ___d abcd abcd
Received:	aaaabbbbccccdddd		a_aab_bbc_cc_ddd

Modulation

- **Implemented:**
  - 4-PSK and BPSK
  - N^2 QAM (but not using due to non-linearities in the speaker-mic combo)





Modulation

Wideband communication – OFDM

- We observed the need to handle wideband setting
- **Fully implemented**
    - Multiple orthogonal subcarrier frequencies
    - Convert multi-tap channel into several single-tap channels

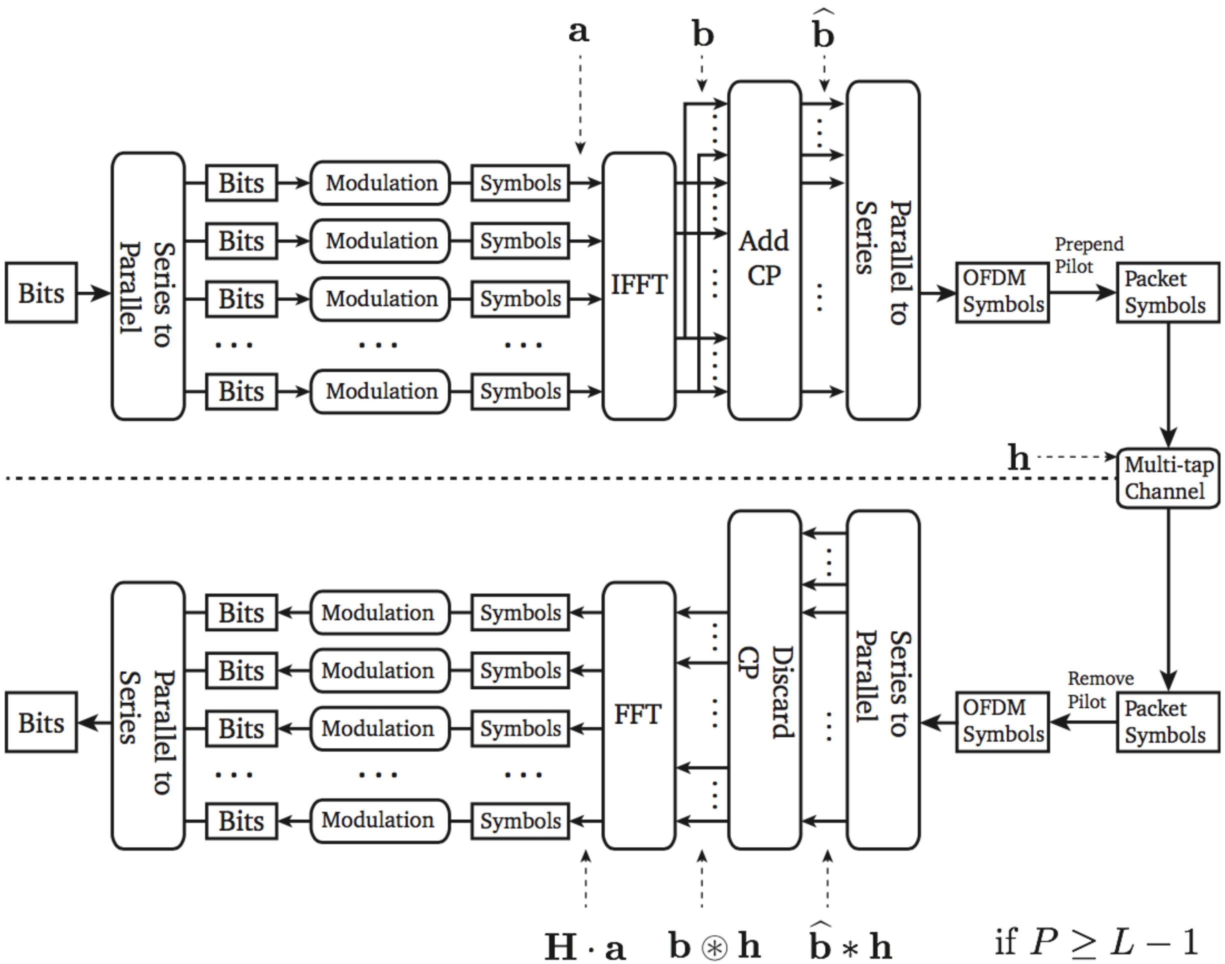
Example:

- a - symbol sequence; b – N point IDFT of a

$$\mathbf{a} \xrightarrow{N\text{-point IDFT}} \mathbf{b} \xrightarrow[\text{with length } P]{\text{add cyclic-prefix}} \widehat{\mathbf{b}} \xRightarrow[\text{with response } \mathbf{h}]{L\text{-tap channel}} \widehat{\mathbf{b}} * \mathbf{h}$$

$$\widehat{\mathbf{b}} * \mathbf{h} \xrightarrow[\text{received symbols}]{\text{discard first } P} (\mathbf{h} \circledast \mathbf{b}) \xrightarrow{N\text{-point DFT}} \mathbf{H} \cdot \mathbf{a}$$

Wideband communication – OFDM



Power Control

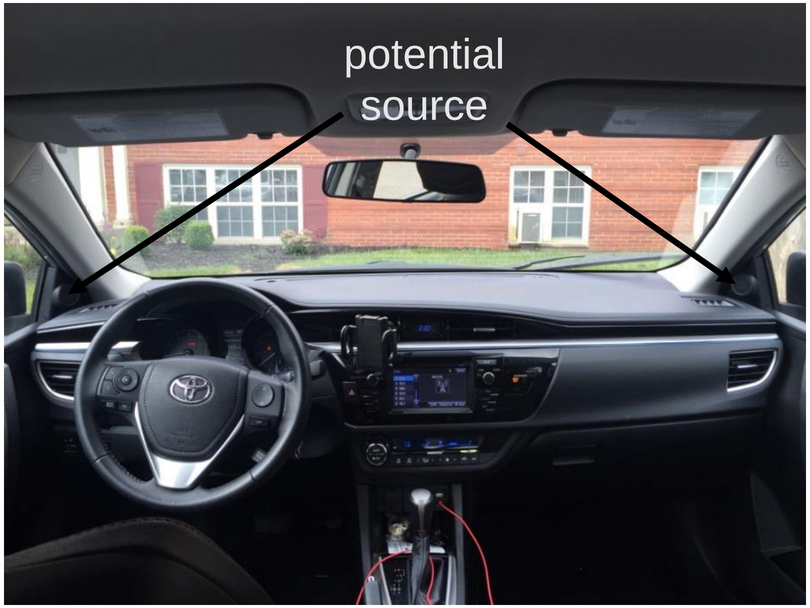
- High power, non-linear distortion
- Low power, low SNR, high error rate

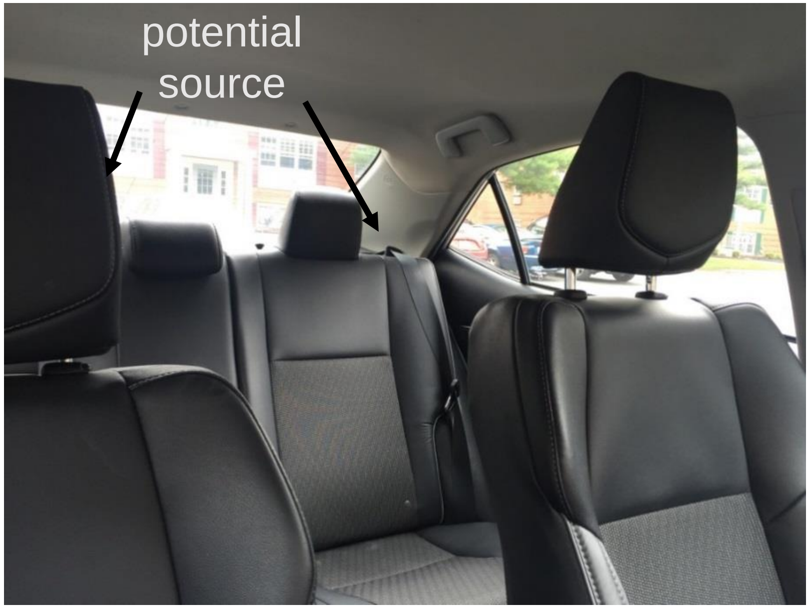
Continuous Transmission

- The receiver should be in continuously check for the presence of a transmission

Channel characterization

- Channel response is determined by the relative locations of potential audio sources, the mic, and the reflectors within the vehicle.
  - important parameters:
    - speed of sound=340.3 m/s
    - wavelength=34cm at 10 kHz; 17cm at 20 kHz. Thus, reflection and diffraction are dominant mechanisms
    - delay spreads ≈ 4-5ms. Thus, 4-5 significant channel taps at 1ksymbol/sec.





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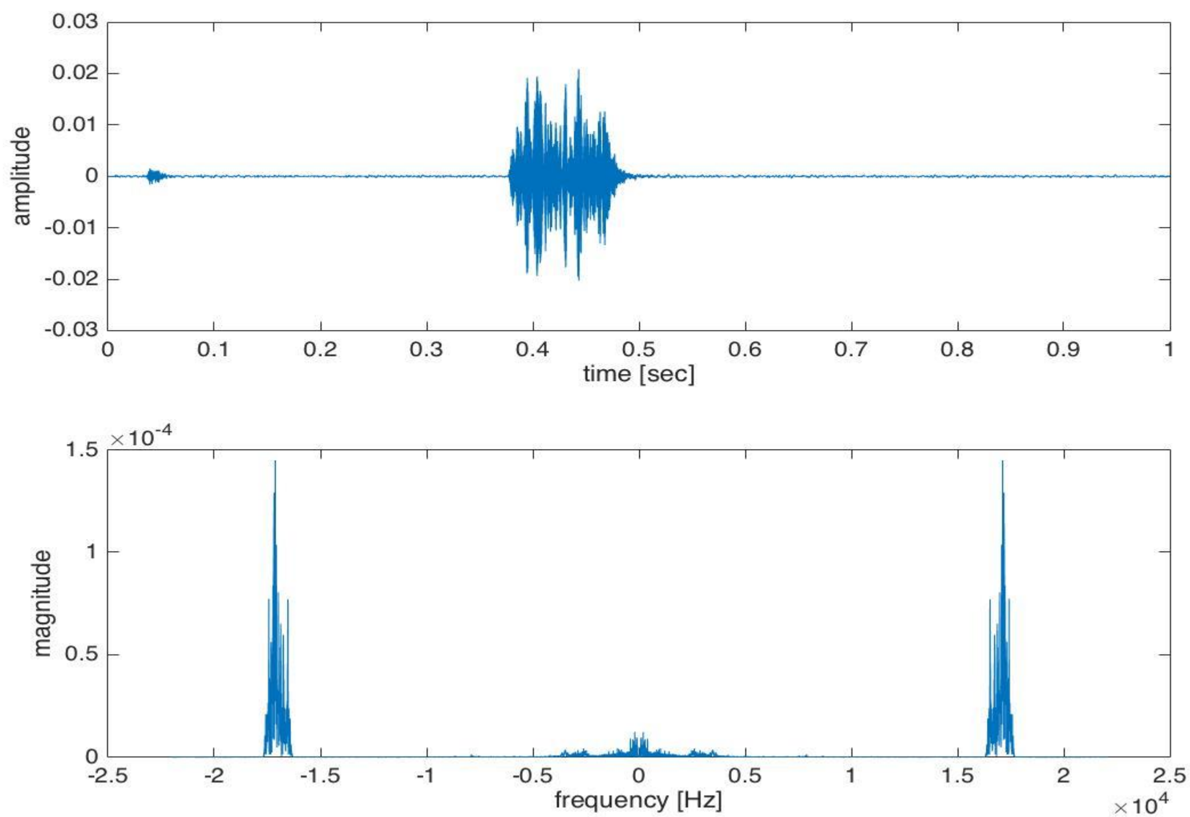
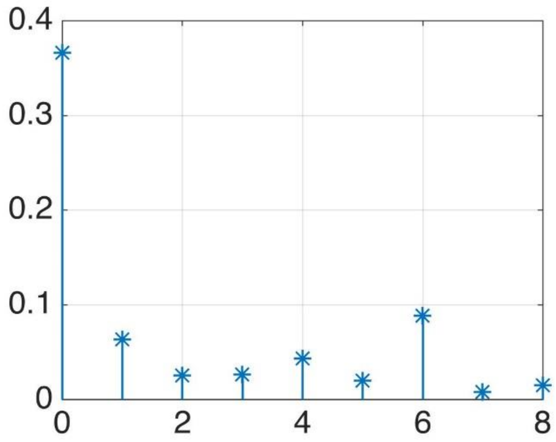
Channel characterization

- Testing with different carrier frequency and symbol rate to learn about channel characterization
- One example: signal length = 1s, fc = 17KHz, symbol rate = 900 sym/sec

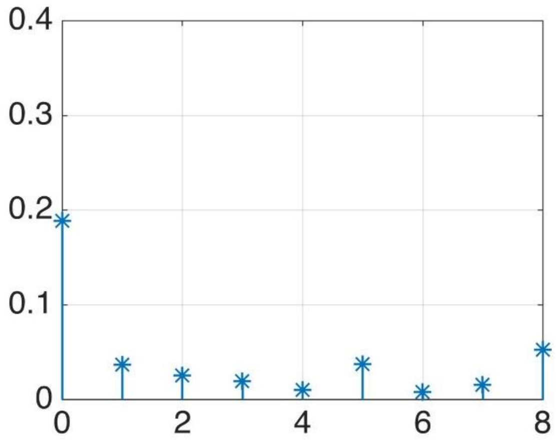


Channel characterization

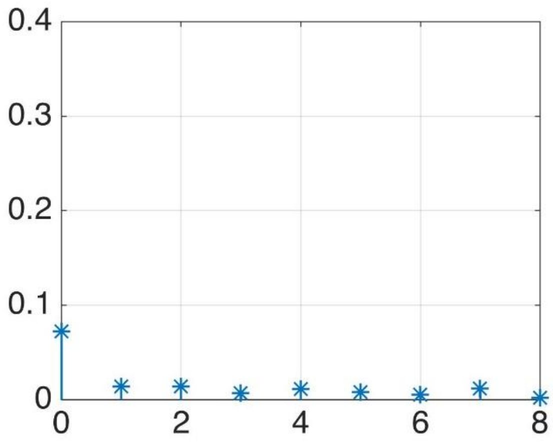
- Channel response of different carrier frequencies
- 150 symbols/second
- Carrier frequency of 17, 18, 19KHz



17KHZ



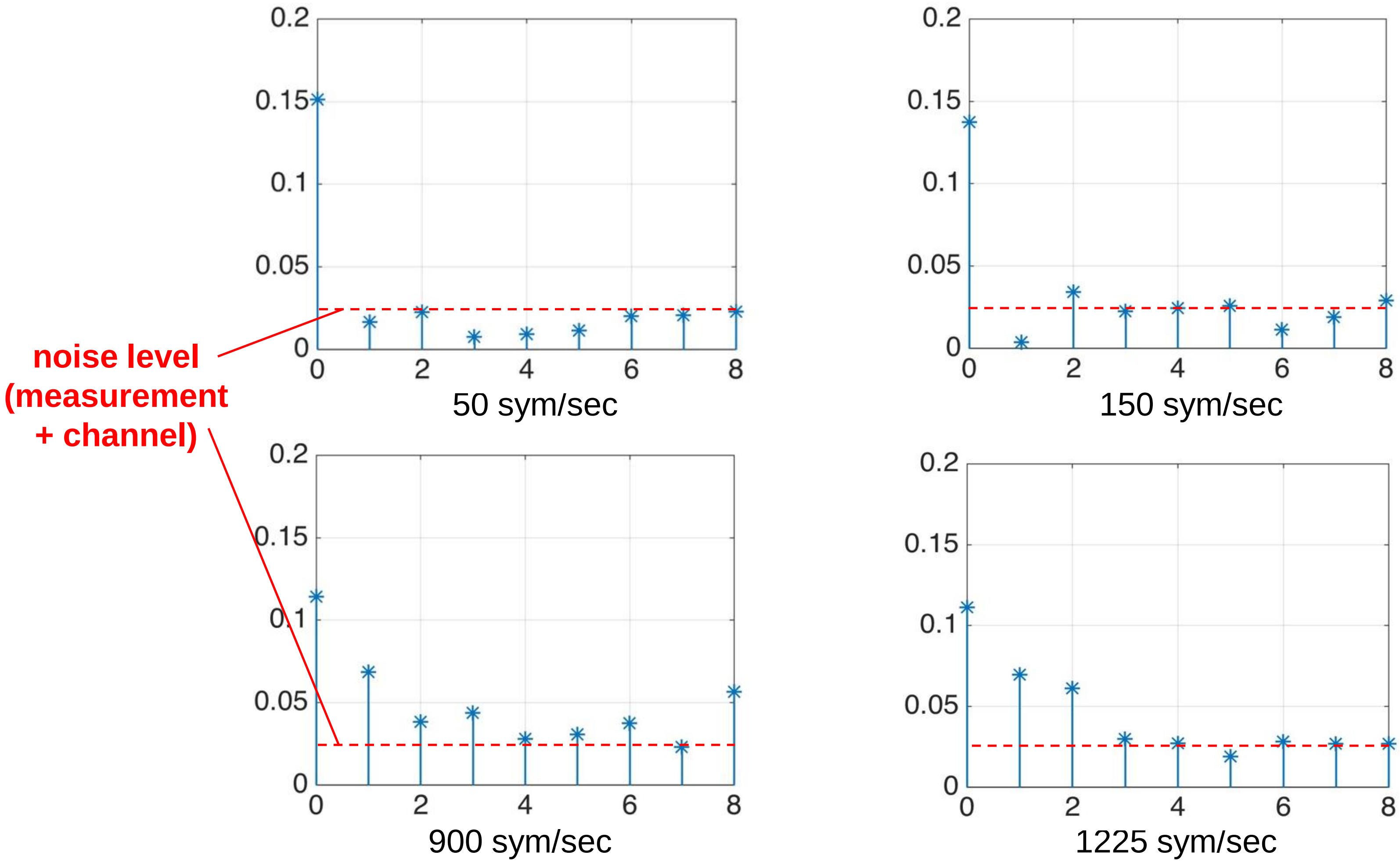
18KHZ



19KHZ

Channel characterization - Signal

- Signal channel response of different symbol rates
- fc = 17kHz



Performance Demonstrations

- We have run experiments in the office and within the vehicle:
- Demo parameters: $f_c = 19\text{kHz},\ \text{rate} = 300\ \text{bits/sec},\ \text{pilot} = 50\ \text{symbols}$
  - **Office (proof of concept):** Continuous broadcast of known text. *Perfect decoding*

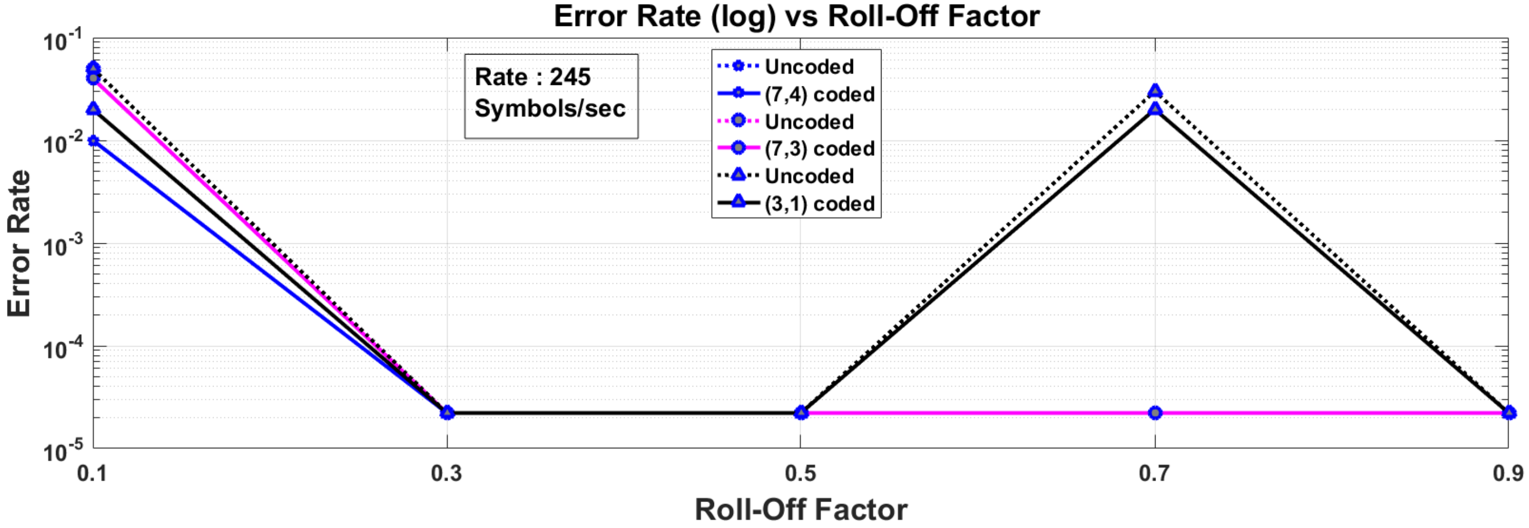
  - **Vehicular setting:** Computer connected to the AUX input and decoded from another computer.
    - Text – receiver at the front seat 
    - Text – receiver at back seat 
    - Randomly generated data 

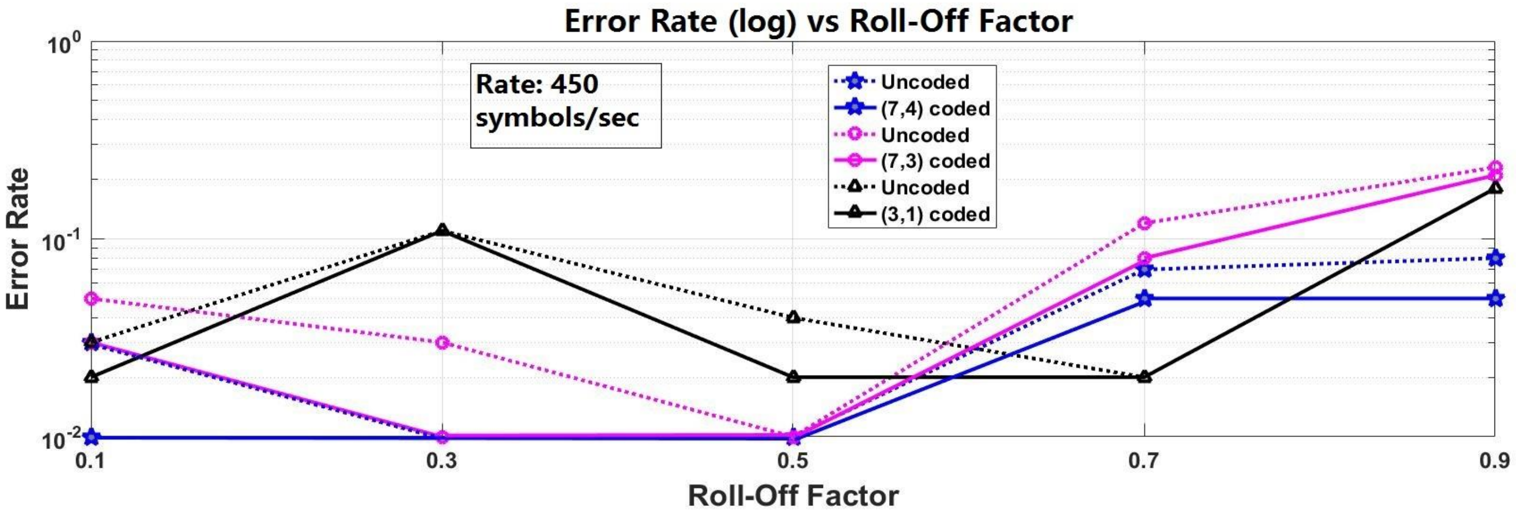
Probability of error ≈ 0.05-0.1

  - Need channel coding to control the error

COMMUNICATION –
ROLL OFF FACTOR TEST

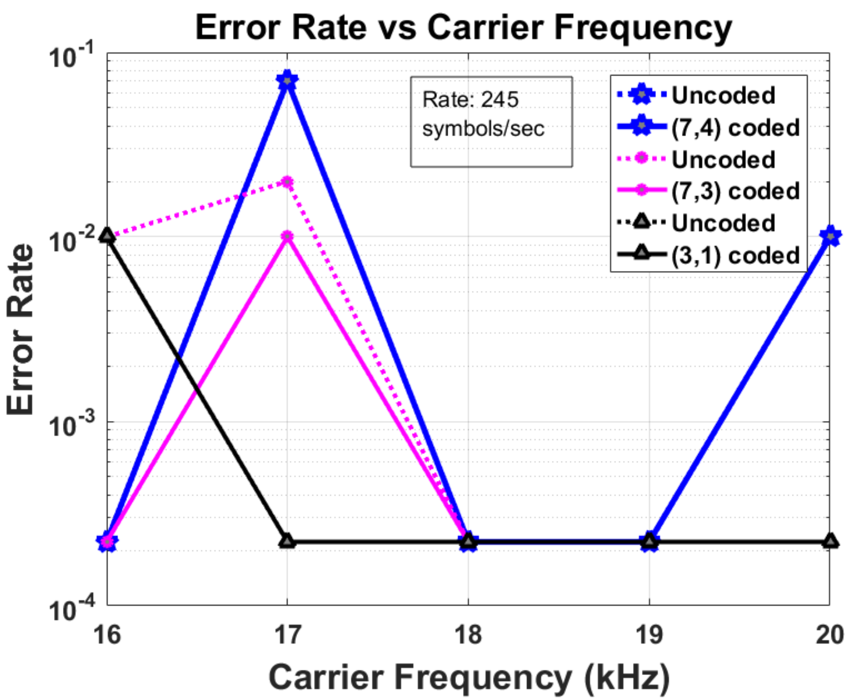
- The Roll off factor (β) was chosen to be 0.5



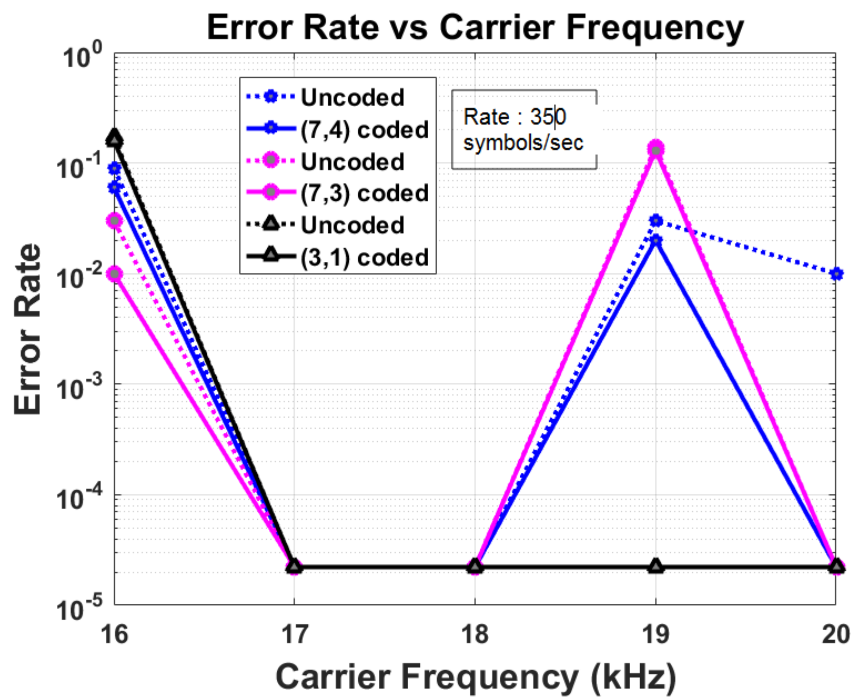


COMMUNICATION -
CHANNEL CODING RESULTS

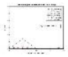
The error rate at different carrier frequencies, with and without channel coding



245 symbols / second

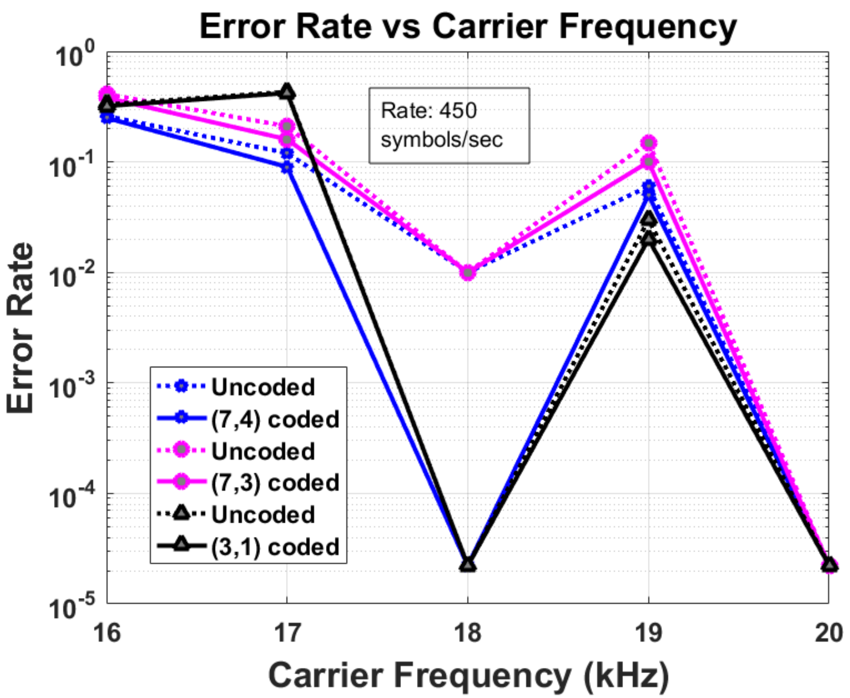


350 symbols / second

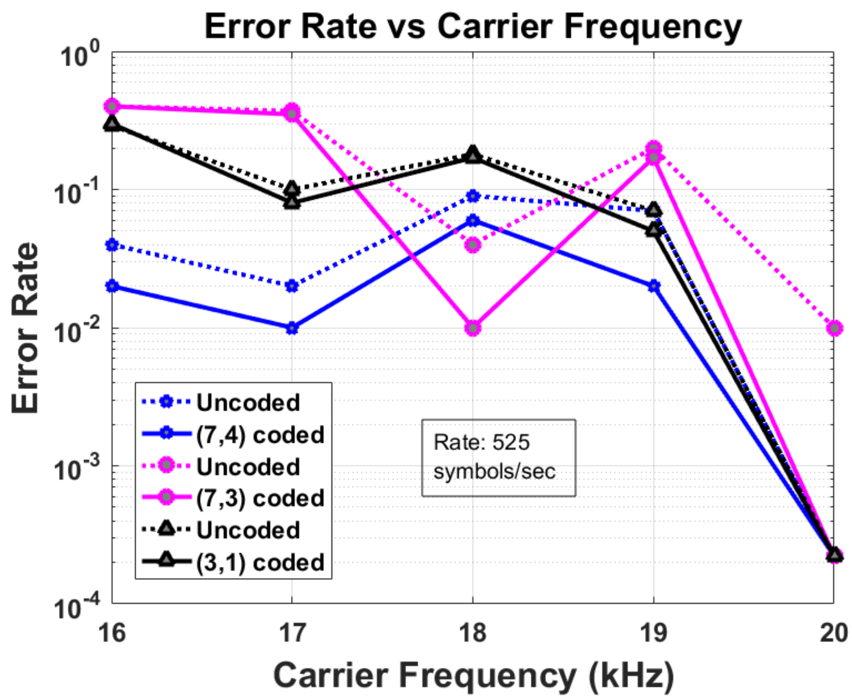


COMMUNICATION -
CHANNEL CODING RESULTS

- The error rate at different carrier frequencies, with and without channel coding
- Less noise is present at higher frequencies



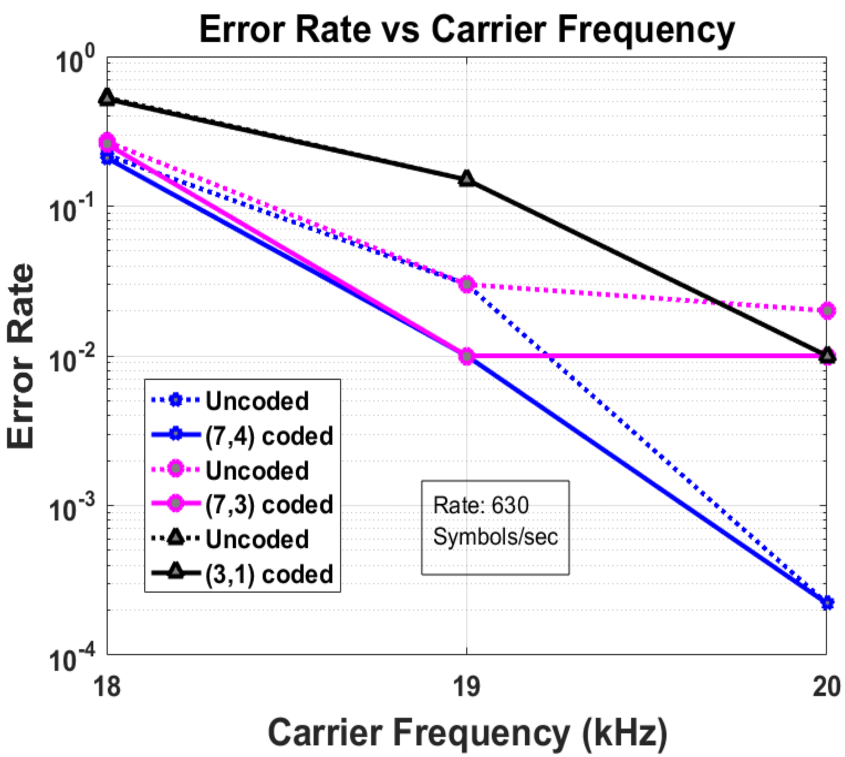
450 symbols / second



525 symbols / second

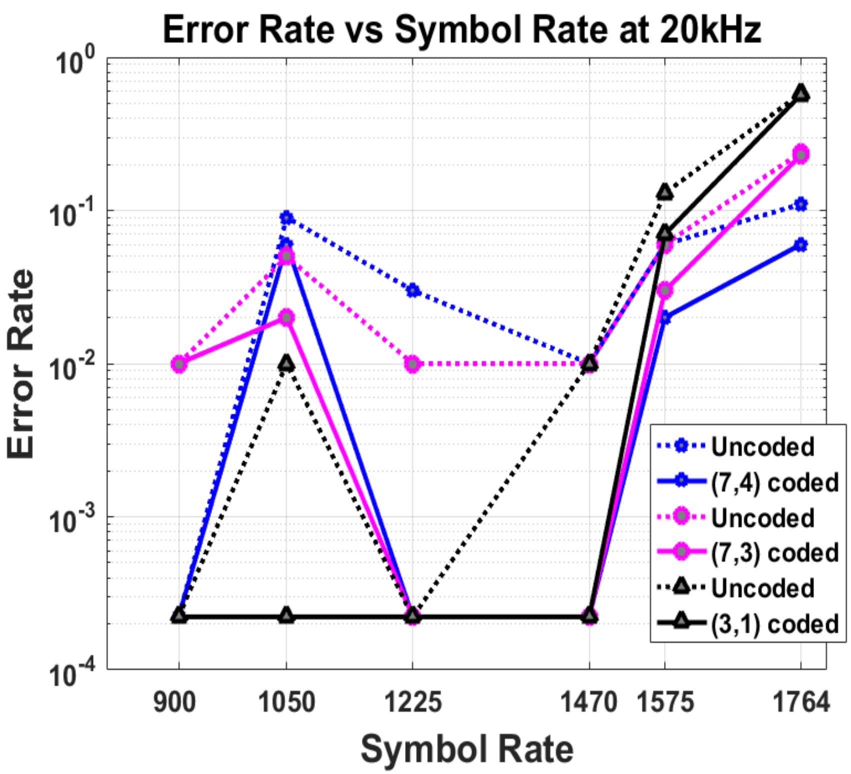
COMMUNICATION – CHANNEL CODING RESULTS

- Symbol rate : 630
- Carrier frequencies (18,19, 20 kHz)
- Least error at 20 kHz



630 symbols / second

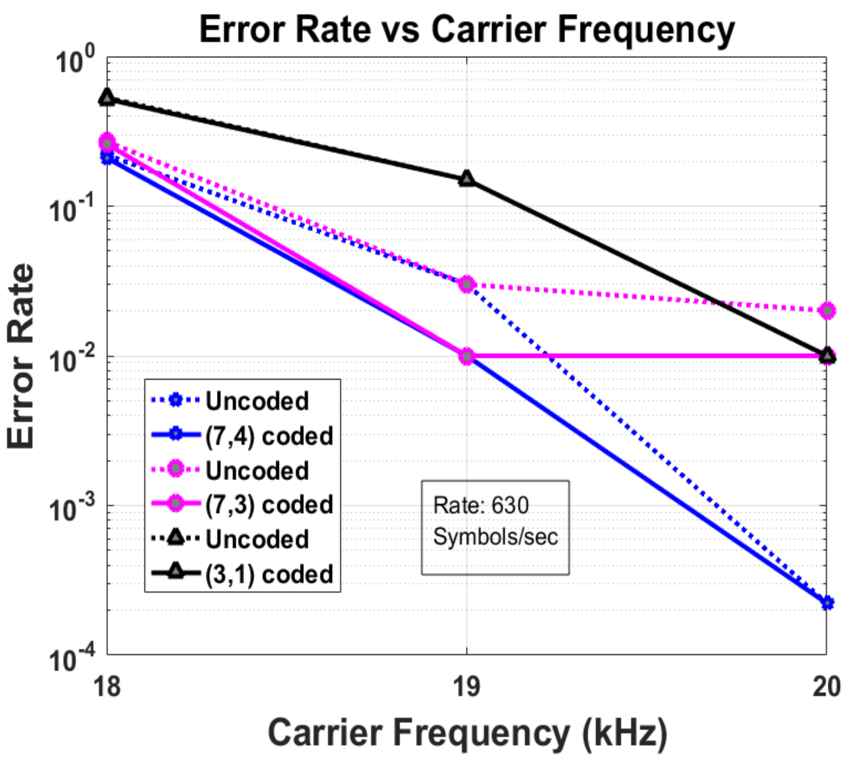
- Carrier frequency = 20 kHz
- Error at different symbol rates



20 kHz carrier frequency

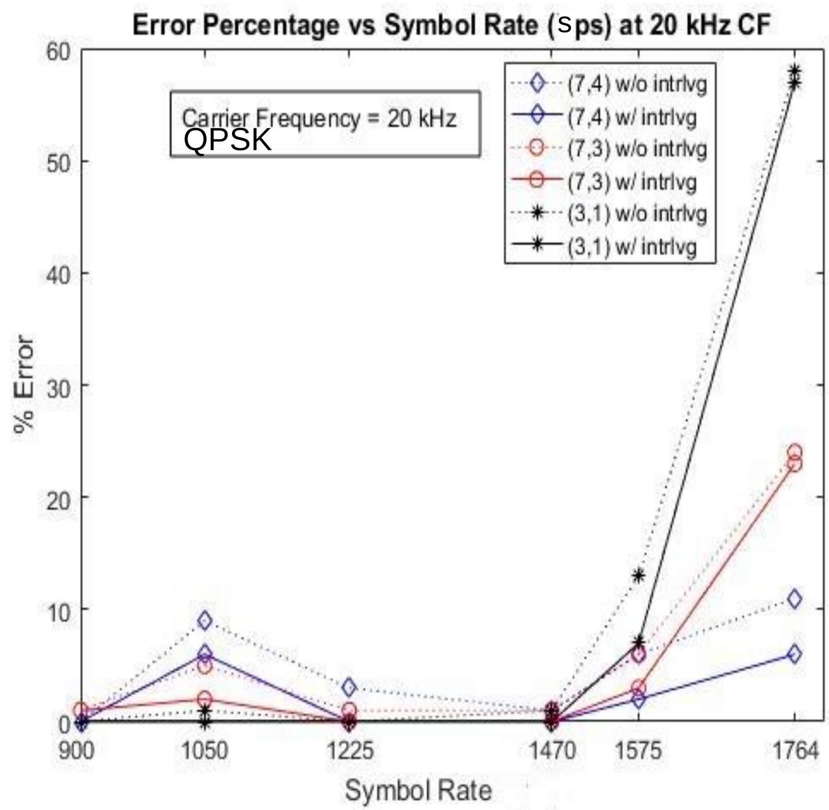
COMMUNICATION – CHANNEL CODING RESULTS

- Symbol rate : 630
- Carrier frequencies (18,19, 20 kHz)
- Least error at 20 kHz



630 symbols / second

- Carrier frequency = 20 kHz
- Error at different symbol rates



20 kHz carrier frequency

Performance Demonstrations with channel coding

- We have run experiments in the office and within the vehicle
- We kept the parameters similar to the last demonstration, but used BPSK modulation instead of QPSK
- Demo parameters: Fc = 19 kHz, 150 symbols /sec, pilot = 50 symbols
  - **Office (proof of concept):** Continuous broadcast of known text. *Perfect decoding*

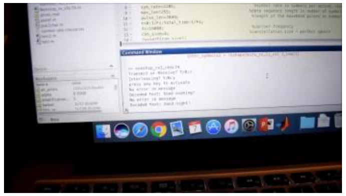
  - **Vehicular setting:** Computer connected to the AUX input, played by the vehicles speakers, and decoded from another computer.
    - Text – receiver at the front seat

    - Text – receiver at back seat

Probability of error ≈ 0

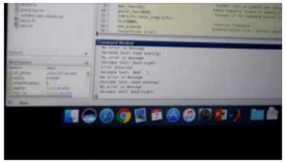
Performance Demonstrations with channel coding

- Demo parameters: Fc = 19 kHz, **2205 symbols /sec**, pilot = 50 symbols
  - **Office (proof of concept):** Continuous broadcast of known text. *Perfect decoding*

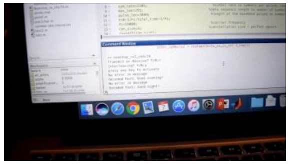


Symbol Rate inside vehicle 350 symbols /sec

- **Vehicular setting:** Computer connected to the AUX input, played by the vehicles speakers, and decoded from another computer.
  - Text – receiver at the front seat



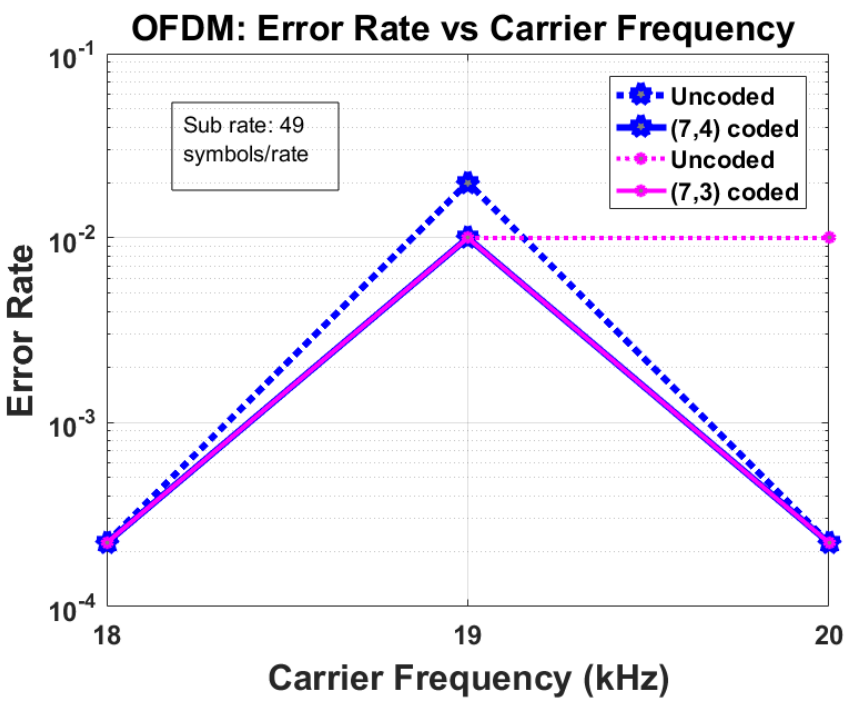
  - Text – receiver at back seat



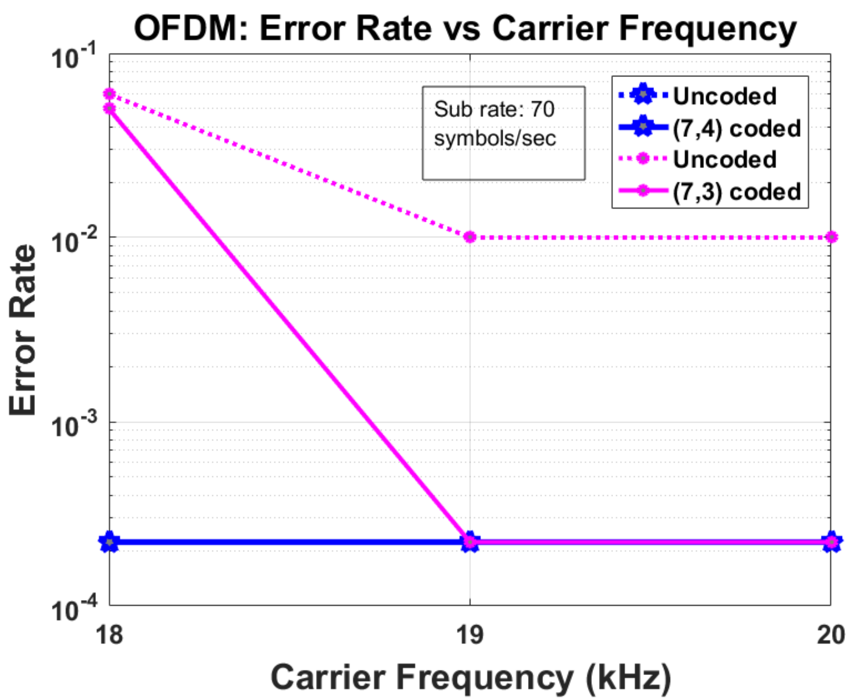
Probability of error ≈ 0

COMMUNICATION -
OFDM WITH CHANNEL CODING RESULTS

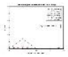
- OFDM with 5 sub channels
- BPSK modulation
- Error shown with and without channel coding



49 symbols / second
Per channel

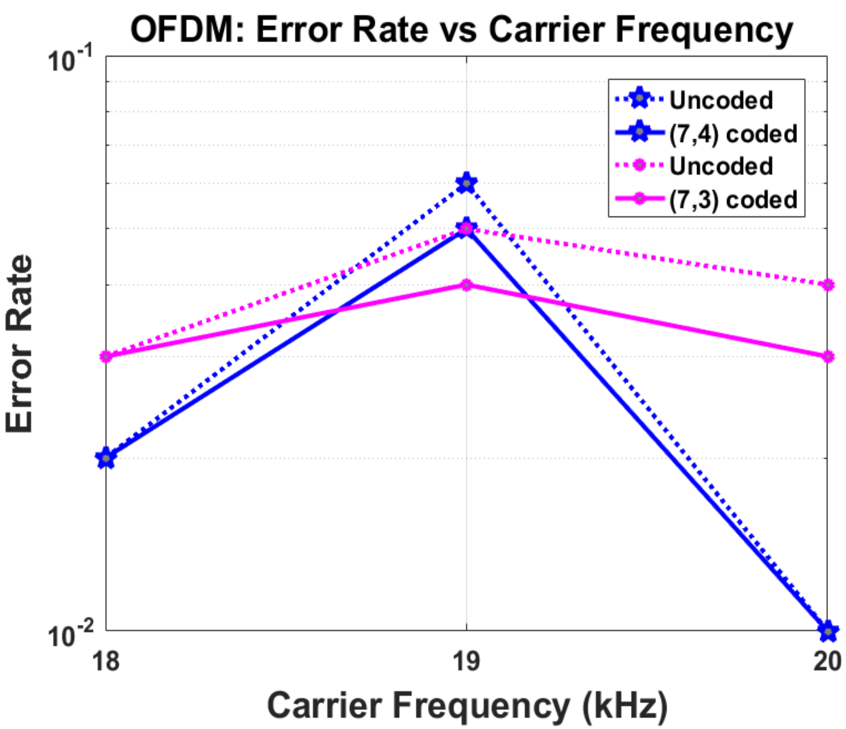


70 symbols / second
Per channel



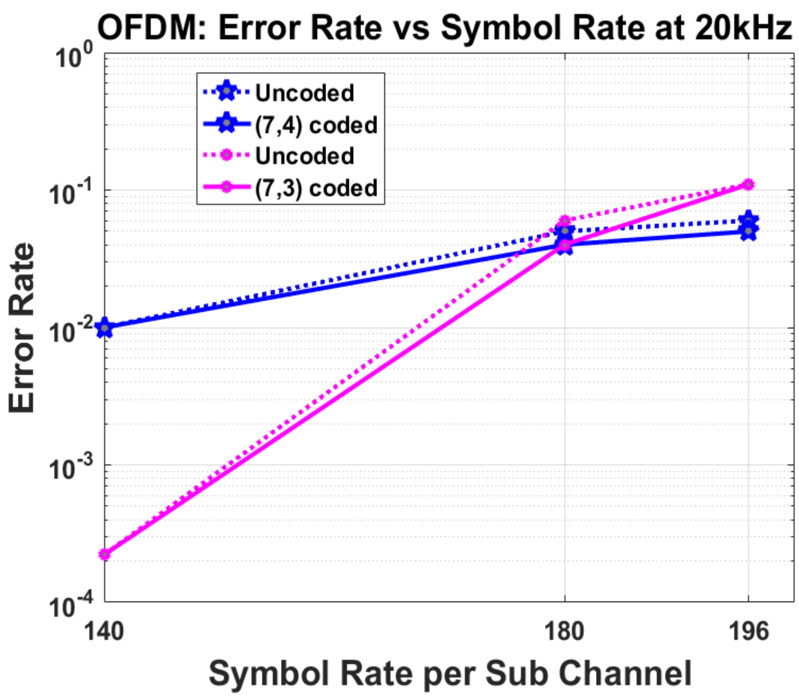
COMMUNICATION - OFDM WITH CHANNEL CODING RESULTS

- 5 Channels
- Symbol rate per channel : 105
- Carrier frequencies (18,19, 20 kHz)
- Least error at 20 kHz



105 symbols / second
Per channel

- Carrier frequency = 20 kHz
- Error shown at different symbol rates per channel
- 5 sub channels

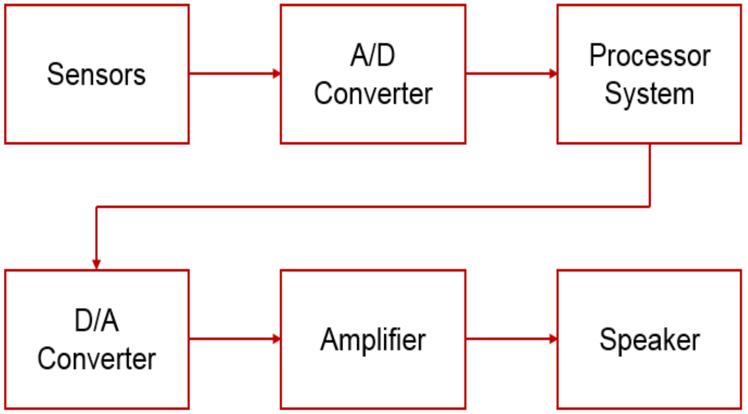


20 kHz carrier frequency

THRUST 2: HARDWARE DESIGN

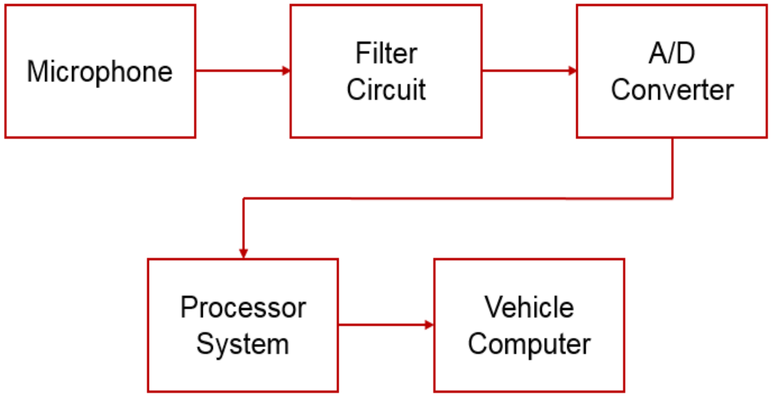
General Design

- A transmitter system to collect analog signals from vehicle sensors, implement transmitter operations, and send it to the **nearest** speaker for broadcasting

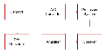


Transmitter

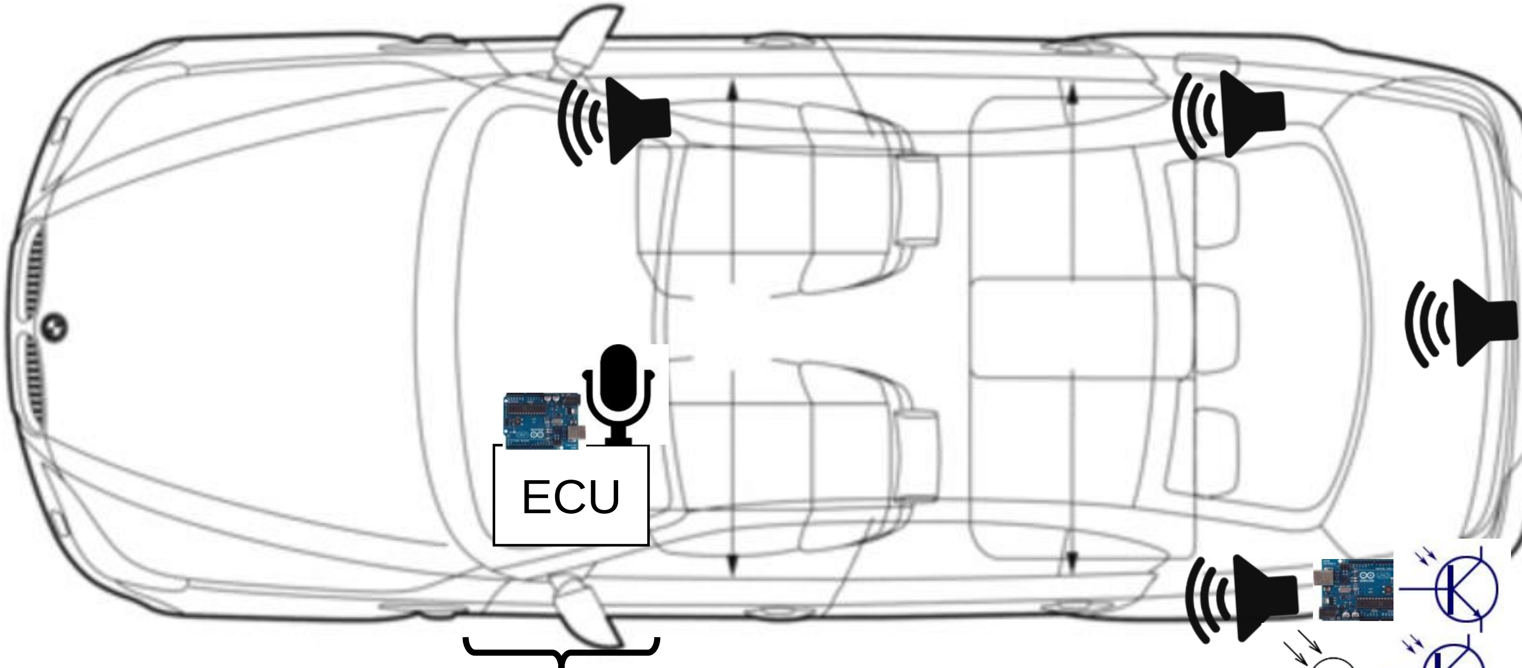
- A receiver system to receive the audio signals, implement receiver operations, and send the data to its designation (e.g. ECU)

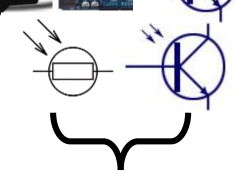


Receiver



HARDWARE COMPONENT





A microphone receives the data at the designation.

Multiple sensors connected to the nearest speaker

The microphone could be placed very close to the speaker to reduce error at higher data transmission rates. One cable is needed.

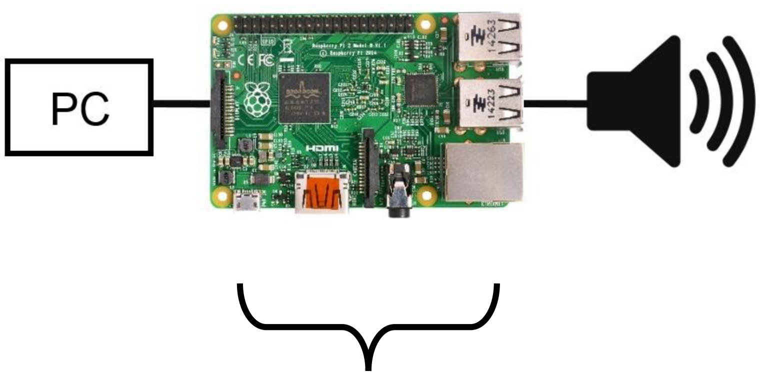
Objectives

- Low Power Consumption
- Robustness with respect to variable conditions
- Long lifetime
- No disturbance to existing systems

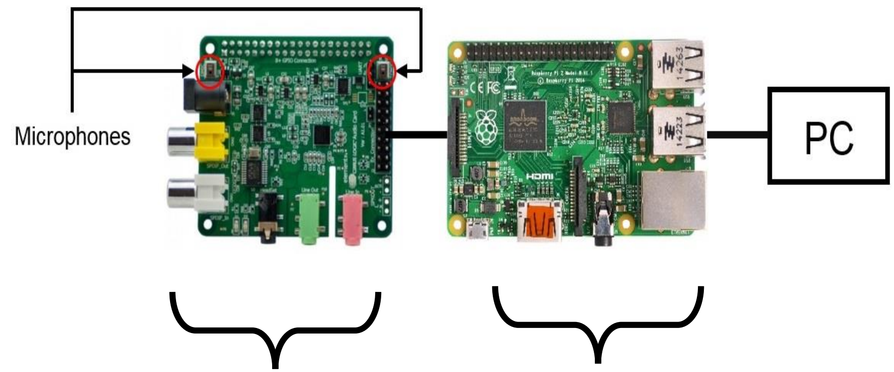
HARDWARE COMPONENT

Current Setup

Transmitter



Receiver



Raspberry Pi 3:

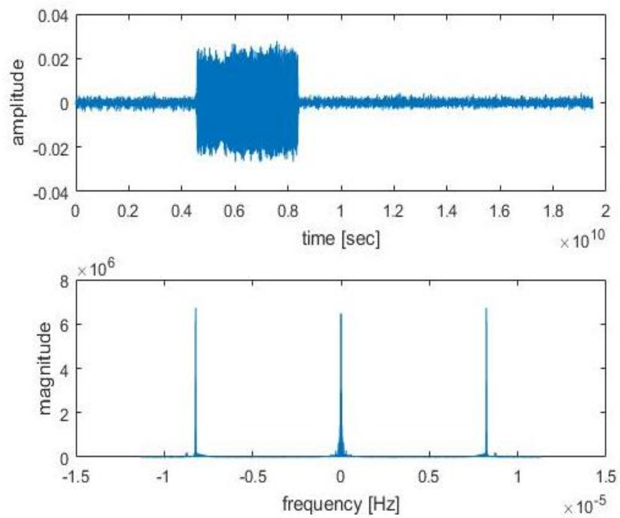
- Quad-core ARM CPU
- 1GB RAM
- 40 pin GPIO port
- 3.5mm audio jack

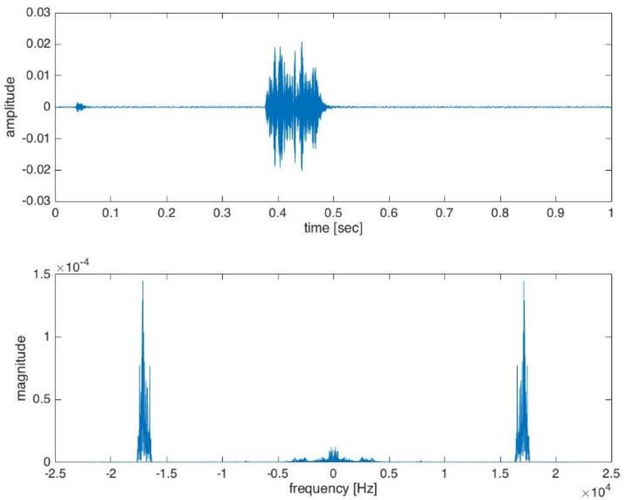
Cirrus Logic Audio Card:

- Compatible with 40 pin GPIO ports on Raspberry Pi.
- Capable of rendering HD Audio at 24-bit, 192kHz

Raspberry Pi 3

Test Result





Test result with signal captured by Raspberry Pi receiver is shown in the figure on the left side, the result of test performed on laptop computer is shown in the figure on the right side.
(carrier frequency = 16 kHz, symbol rate = 50 symbols/sec)

FUTURE STEPS

- Extensive evaluation with built in hardware under a variety of conditions (with mobility, exterior noise, etc.)
- Extend the mobile app for various other applications. One example is secret key sharing for encrypted intra-vehicular communication
- Expand the set of codes to a more robust larger block codes
- Examining efficient placement of speakers and microphones to reduce costs
- Full prototyping

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