# Session B.3 Spectrum Efficient Technologies






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# On the Performance of SCCC CPM-OFDM(A) Schemes for Aeronautical Telemetry

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**Invited Presentation**
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# Outline of Presentation

- Introduction/Motivation
- Continuous Phase Modulation Basics
- DFT-Precoded OFDM(A)
- CPM + DFT-Precoded OFDM(A) ←→ CPM-OFDM(A)
- SCCC CPM-OFDM(A):  the PCM/FM variant
- Frequency Domain Equalization in Frequency Selective Fading
- Performance in Aeronautical Telemetry Radio Channels
- Conclusions

# Introduction (T&E Need)

- Spectrally efficient modulations to support transmission of real-time data from test vehicles to the ground
  - Existing telemetry bands are operating at or close to capacity
- New modulations that can be used with power efficient nonlinear amplifiers
  - Conventional waveforms can be used with Class "C" nonlinear amplifiers
  - Modulations requiring little or no input back off power from saturation
- New modulations and schemes supporting exponential growth in data rates
  - Today's applications require data rates ~ 10's of Megabits / sec
- Low complexity equalization to mitigate effects of frequency selective fading
  - Fading is a leading cause of data loss in aeronautical telemetry

# Introduction/Motivation

- In an ideal world, we would have a transmission scheme which had
  - ✓ High Power Efficiency
  - ✓ High Spectral Efficiency
  - ✓ Robust to Multipath
  - ✓ Low Complexity Transceiver Implementation

- This presentation discusses a hybrid modulation scheme which combines two popular modulations (Continuous Phase Modulation and DFT-precoded OFDMA) in order to achieve these objectives

- CPM is widely used for telemetry applications due to its constant envelope property→power efficiency and smooth phase transitions→ spectral efficiency

- DFT-precoded OFDM(A) is used in wireless communications (eg., LTE uplink) for its spectral efficiency and higher power efficiency than conventional OFDM(A)

# CPM Basics

- The complex base-band equivalent of a CPM signal is written as

$$s(t) = e^{j\phi(t,\alpha)}$$

- where the phase has the form

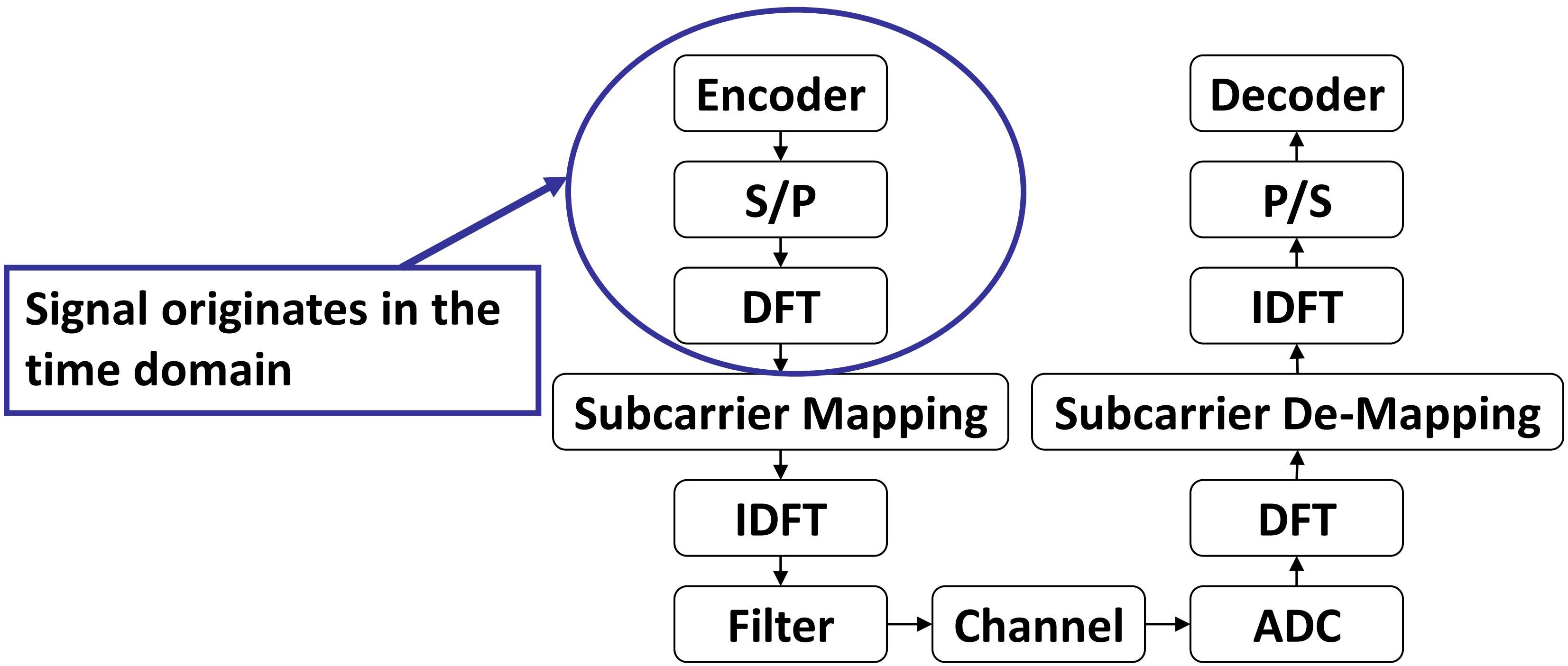
$$\phi(t,\alpha) = 2\pi h \sum_{i=0}^{L-1} \alpha_{n-i} q(t-(n-i)T) + \left[ \pi h \sum_{i=-\infty}^{n-L} \alpha_i \right] \mathrm{mod}\, 2\pi$$

- In the above, $\alpha$ are *M*-ary data symbols and *h* is the modulation index. The phase pulse $q(t)$ is normalized such that

$$q(t) = \begin{cases} 0 & t \le 0 \\ 1/2 & t > LT \end{cases}$$

# DFT Pre-coded OFDM(A)

- DFT pre-coded OFDM(A) is a modulation format in which data is spread over multiple sub-carriers but transmitted in single-carrier format, which reduces the Peak to Average Power Ratio (PAPR) relative to conventional OFDMA
  - PAPR still higher than CPM



# CPM + DFT Pre-coded OFDMA

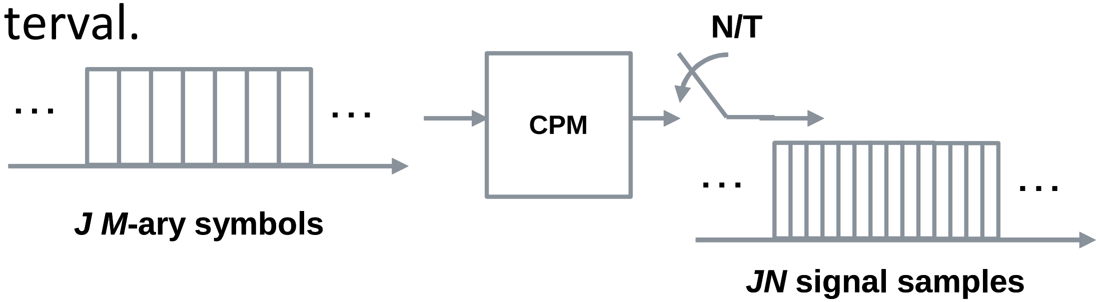
- OFDM(A) and CPM each have their own advantages and disadvantages.

- Our perspective:
    - Develop an advanced modulation scheme which offers some of the key benefits of both.

  – Ideally, this new modulation should have:
    - Higher power efficiency than OFDMA
    - Lower equalization complexity than CPM
    - Higher immunity to multiple access interference than CPM
    - Higher frequency agility than CPM → spectral efficiency

# Where Do We Start?

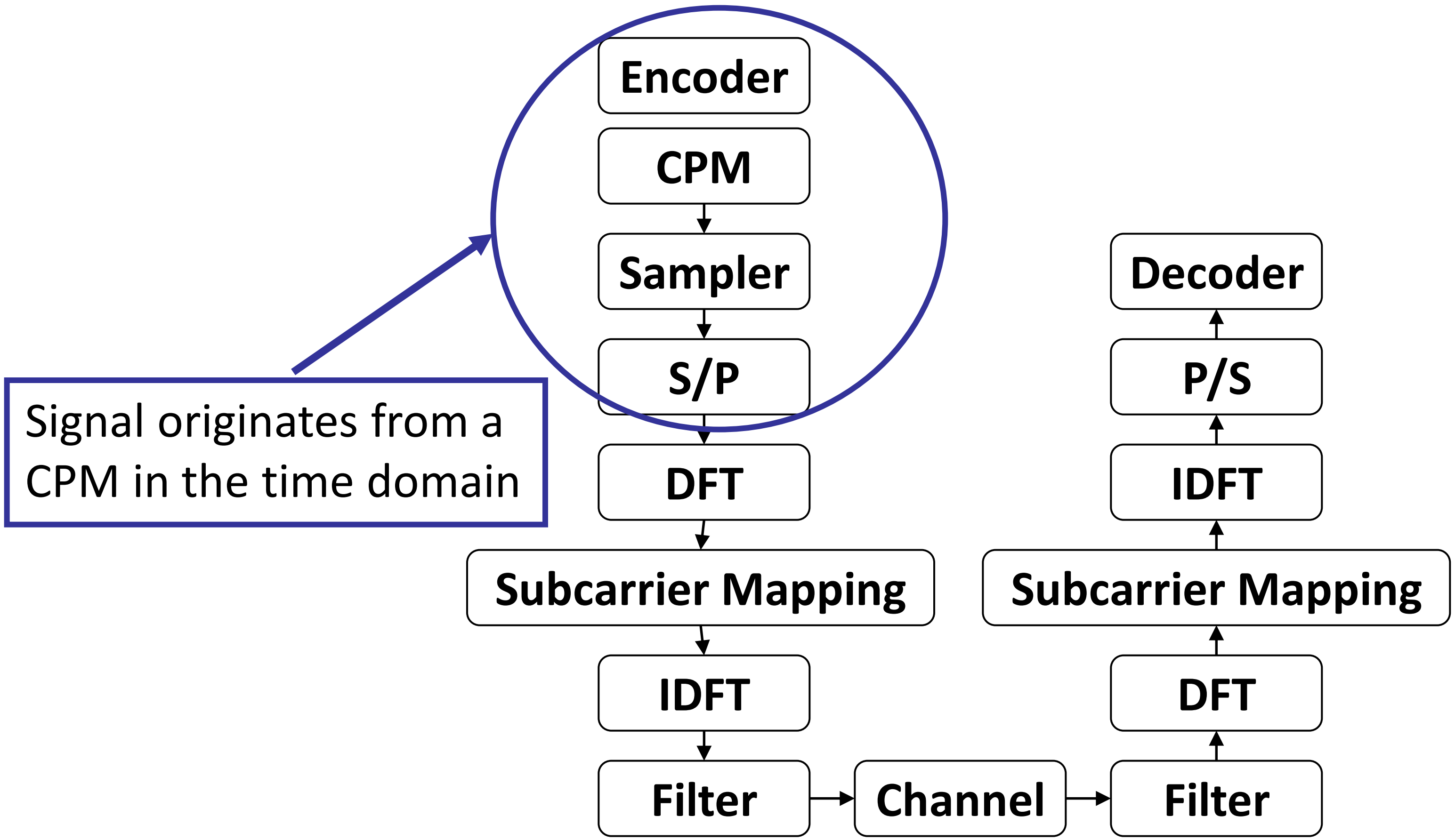
- We know that
  - CPM is a constant modulus *continuous-time* waveform, but…
  - An OFDM(A) transmitter processes blocks of data *symbols*.
- Assume that we continuous-phase modulate *J M*-ary symbols (symbol rate *T*) and then *sample* the resulting waveform at a rate of *N* times per symbol interval.




- The resulting *JN* signal samples always retain the constant modulus property of the input waveform → power efficiency.
- If we can send those CPM signal samples using multiple sub-carriers, we have now adopted some of the spectral efficiency of DFT pre-coded OFDM(A).
  - If the performance for N = 1 is good, then we have also maximized the spectral efficiency of this scheme.

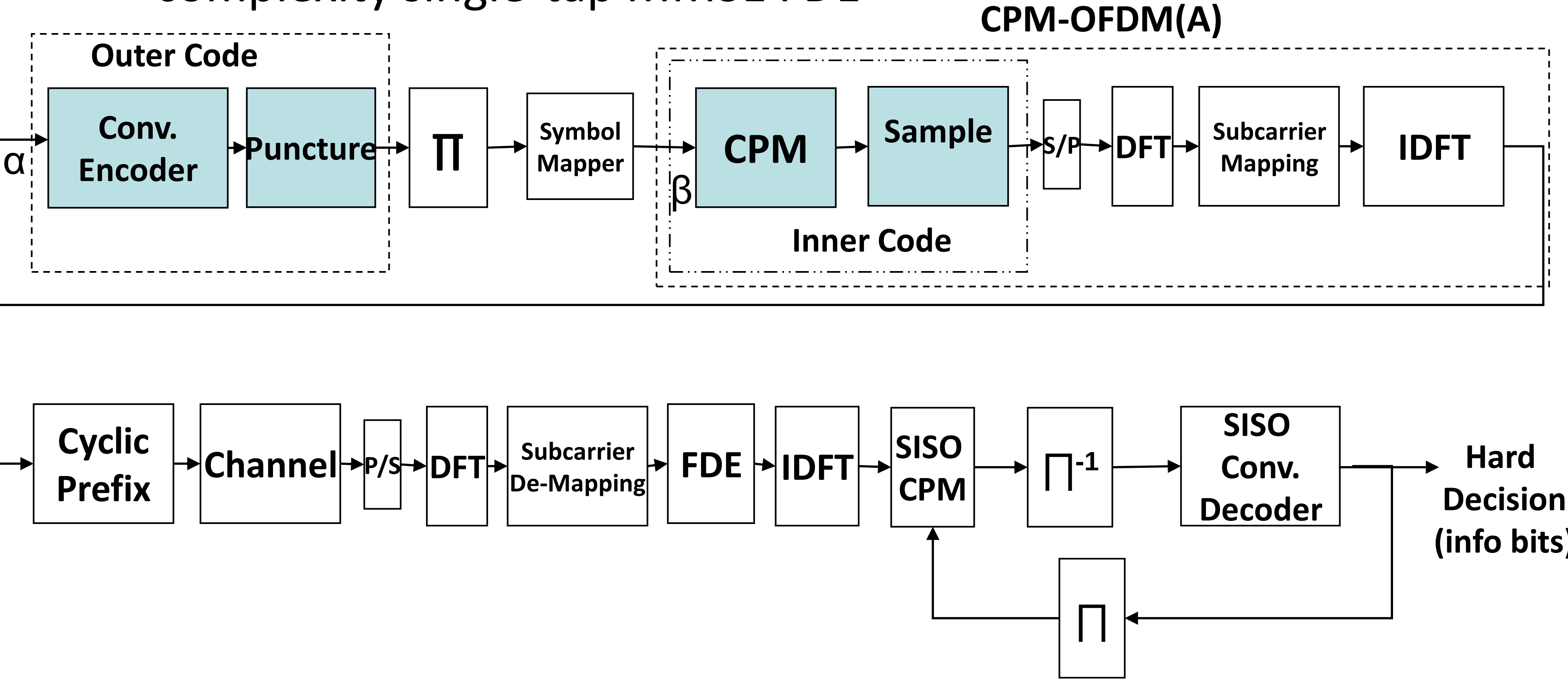
# CPM-OFDM(A)

- From an OFDM(A) perspective, we can treat the CPM signal samples just like conventional symbols (QPSK, 16-QAM, etc.)



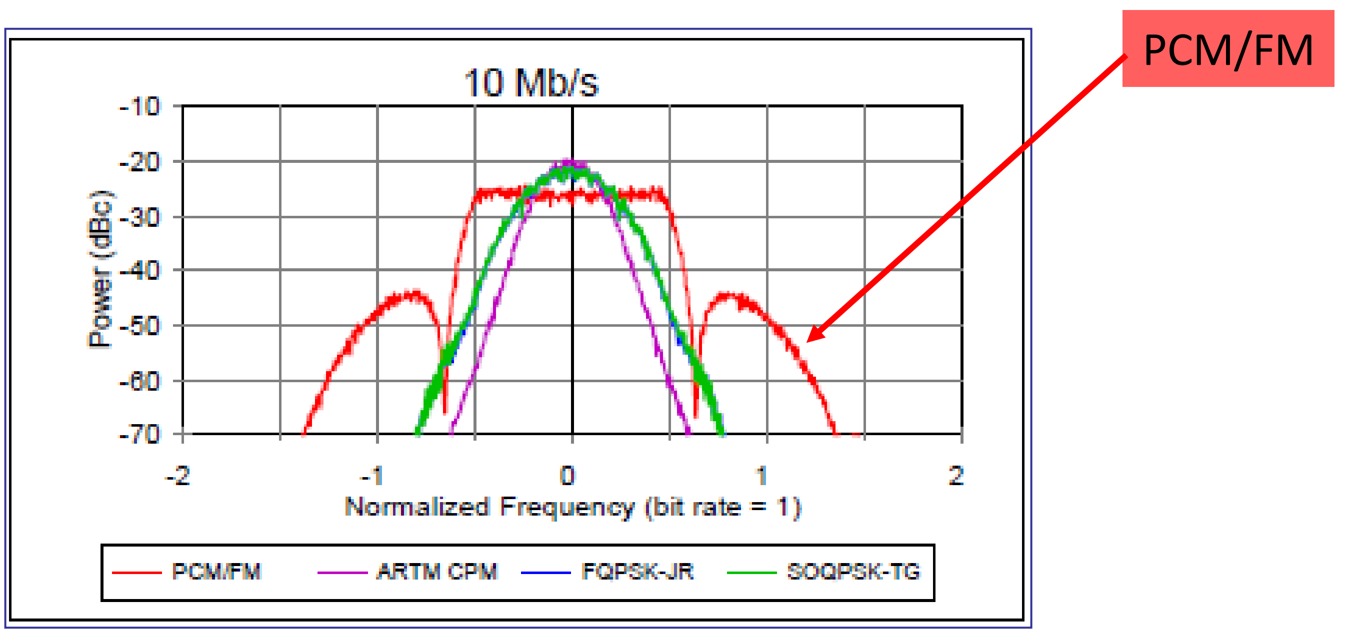
# SCCC CPM-OFDM(A)

- Over frequency selective fading channels, we can also improve performance by using a SCCC CPM-OFDM(A) scheme
- Use SISO CPM and SISO Convolutional decoding following low complexity single-tap MMSE FDE



# SCCC CPM-OFDM(A) with PCM/FM

- PCM/FM is a binary <u>single carrier</u> Continuous Phase Modulation (CPM) that has been widely adopted by the telemetry community
- Good detection efficiency but is actually the <u>least spectrally efficient</u> of the telemetry waveforms
- Guard bands are needed due to adjacent channel interference
- **<u>Simply "plug in" the PCM/FM modulator into the CPM portion of the CPM-OFDM(A)</u>**

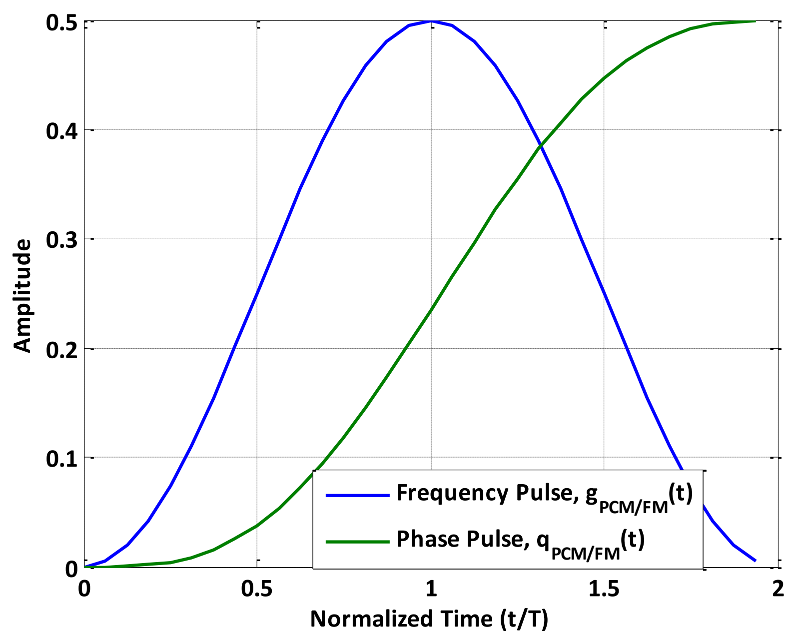


# PCM/FM CPM Parameters

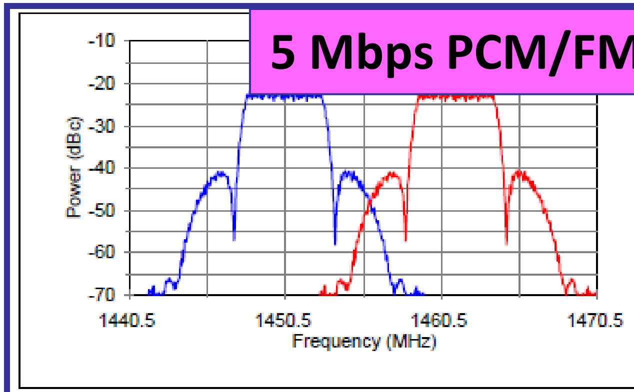
- Modulation index $h$ = 7/10; Signal memory, $L$ = 2
- Raised Cosine Pulse Shaping

**PCM/FM Pulse Shaping**

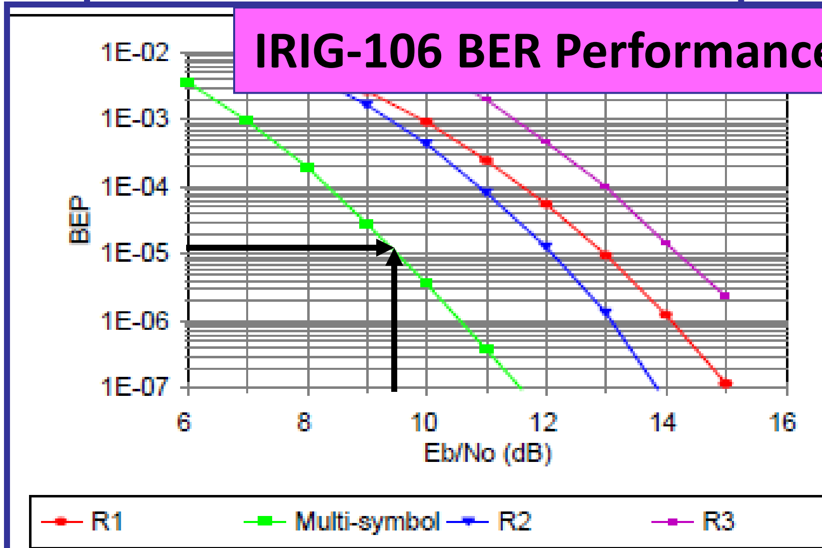
$$F_{RC}(t) = \begin{cases} \frac{1}{2LT}\left(1-\cos\frac{2\pi t}{LT}\right) & 0 \le t < LT \\ 0 & else \end{cases}$$




**5 Mbps PCM/FM**

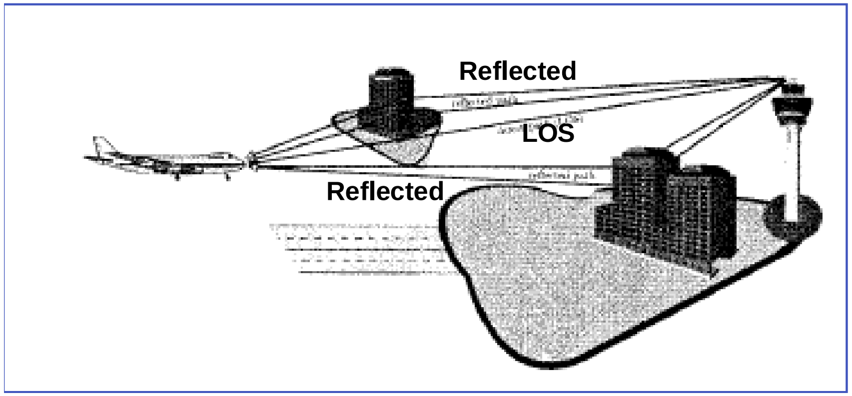



**IRIG-106 BER Performance**

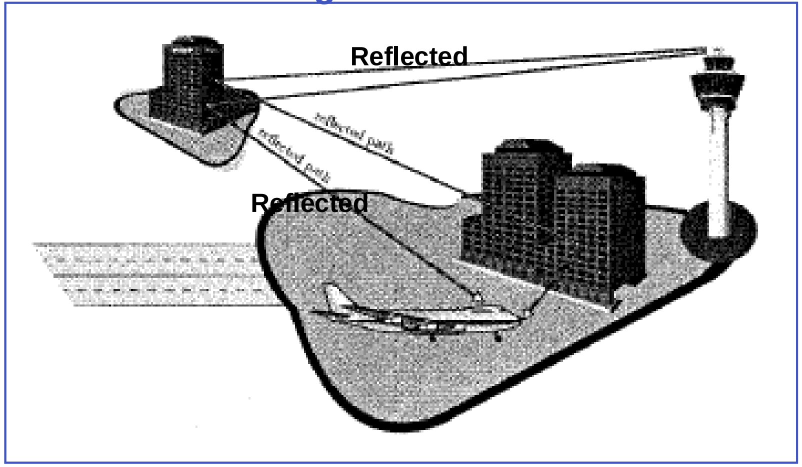


# Telemetry Channel Models

## Multi-path Propagation for Arrival Scenarios




## Multi-path Propagation for (Worst Case) Parking Scenarios



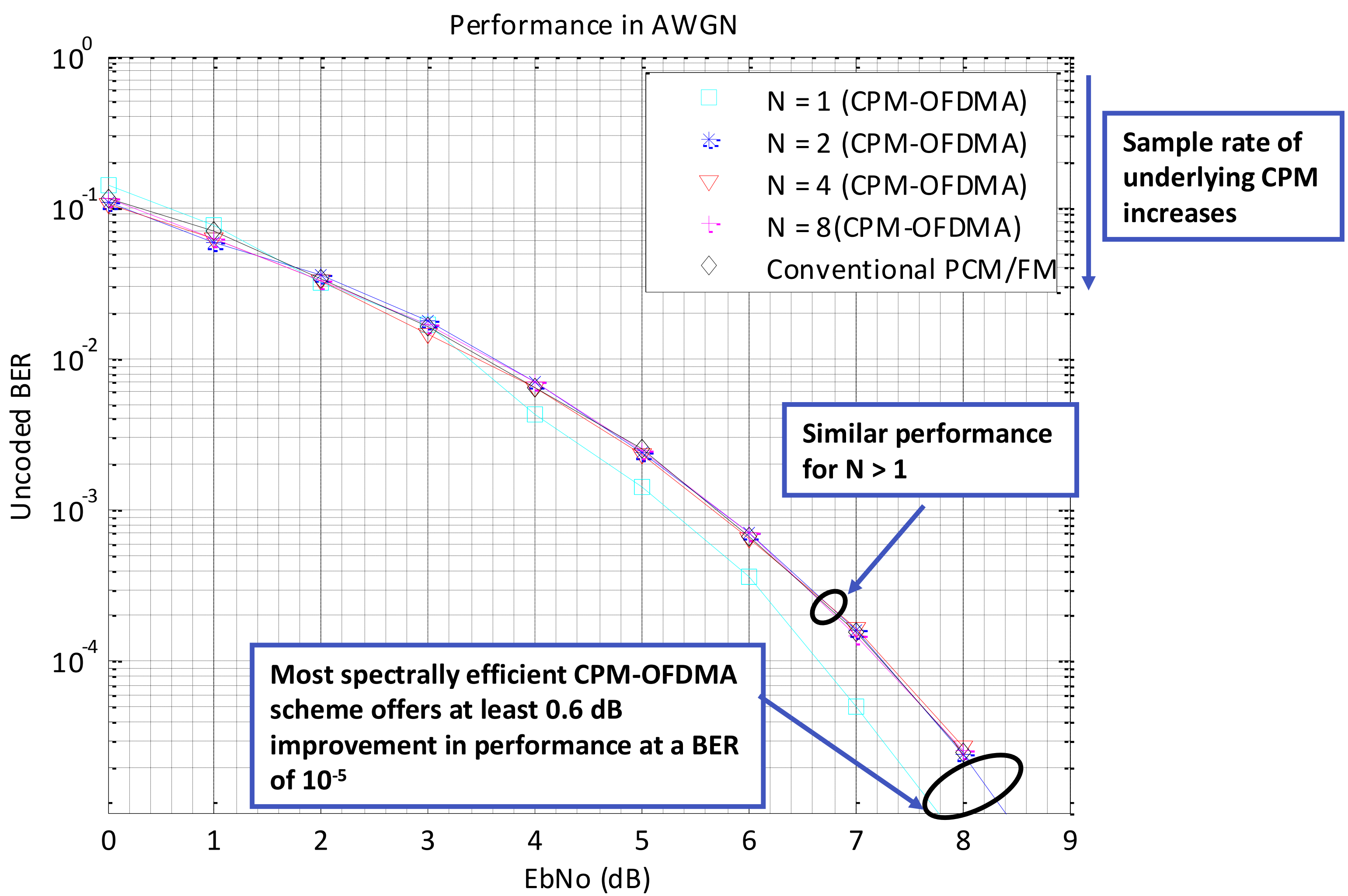

**Typical and Worst Case Parameters for Aeronautical Channels [1]**

| | Parking scenario | Taxi scenario | Arrival scenario | En-Route scenario |
|---|---|---|---|---|
| Aircraft velocity $v$ [m/s] | 5.5<br>$0 \dots 5.5$ | 15.0<br>$0 \dots 15$ | 150.0<br>$25 \dots 150$ typ. 85 | 440.0 (620.0)<br>$17 \dots 440$ typ. 250 |
| Maximum delay $\tau_{max}$ [s] | $7.0 \cdot 10^{-6}$ | $0.7 \cdot 10^{-6}$ | $7.0 \cdot 10^{-6}$ | $33.0 \cdot 10^{-6}$ ($66.0 \cdot 10^{-6}$)<br>$6 \cdot 10^{-6} \dots 200 \cdot 10^{-6}$ |
| Number of echo paths $N$ | 20 | 20 | 20 | 20 |
| Rice factor $K_{Rice}$ [dB] | - | 6.9 | 15.0<br>$9 \dots 20$ | 15.0<br>$2 \dots 20$ |
| $f_{D_{LOS}}/f_{D_{max}}$ factor | - | 0.7 | 1.0 | 1.0 |
| Start angle $\varphi_{a_L}$ of beam [°] | 0.0 | 0.0 | −90.0 | 178.25 |
| End angle $\varphi_{a_H}$ of beam [°] | 360.0 | 360.0 | +90.0 | 181.75 |
| Exponential or two-ray delay | exp | exp | exp | two-ray |
| Slope time $\tau_{slope}$ [s] | $1.0 \cdot 10^{-6}$ | $1/9.2 \cdot 10^{-6}$ | $1.0 \cdot 10^{-6}$ | - |

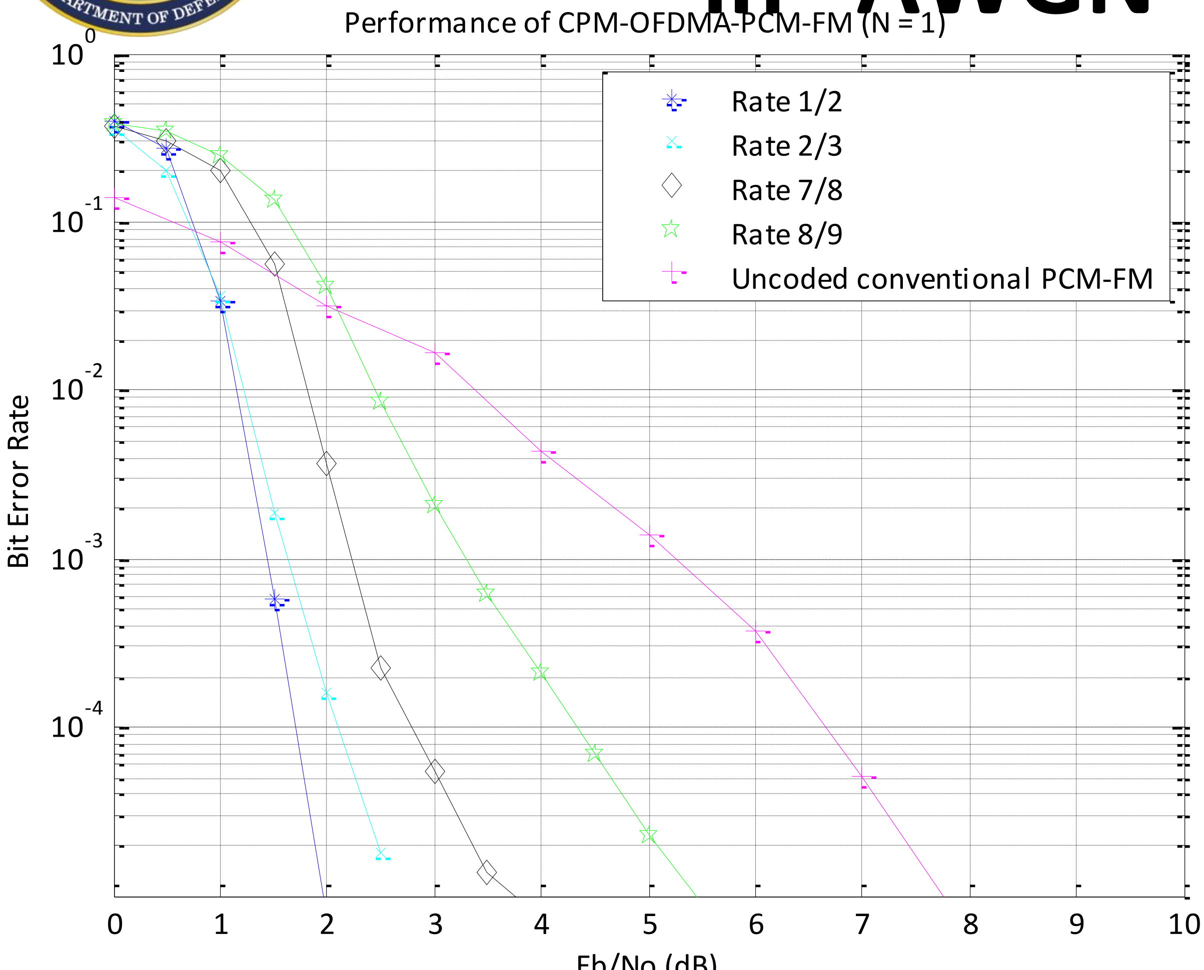
**We have simulated the arrival and parking scenarios with a Doppler of 0 (to represent minimal vehicle speed or 0 m/s)**

**[1]** E. Haas, "Aeronautical Channel Modeling", IEEE Transactions on Vehicular Technology, Vol. 51, No. 2, March 2002.

# Uncoded Performance in AWGN



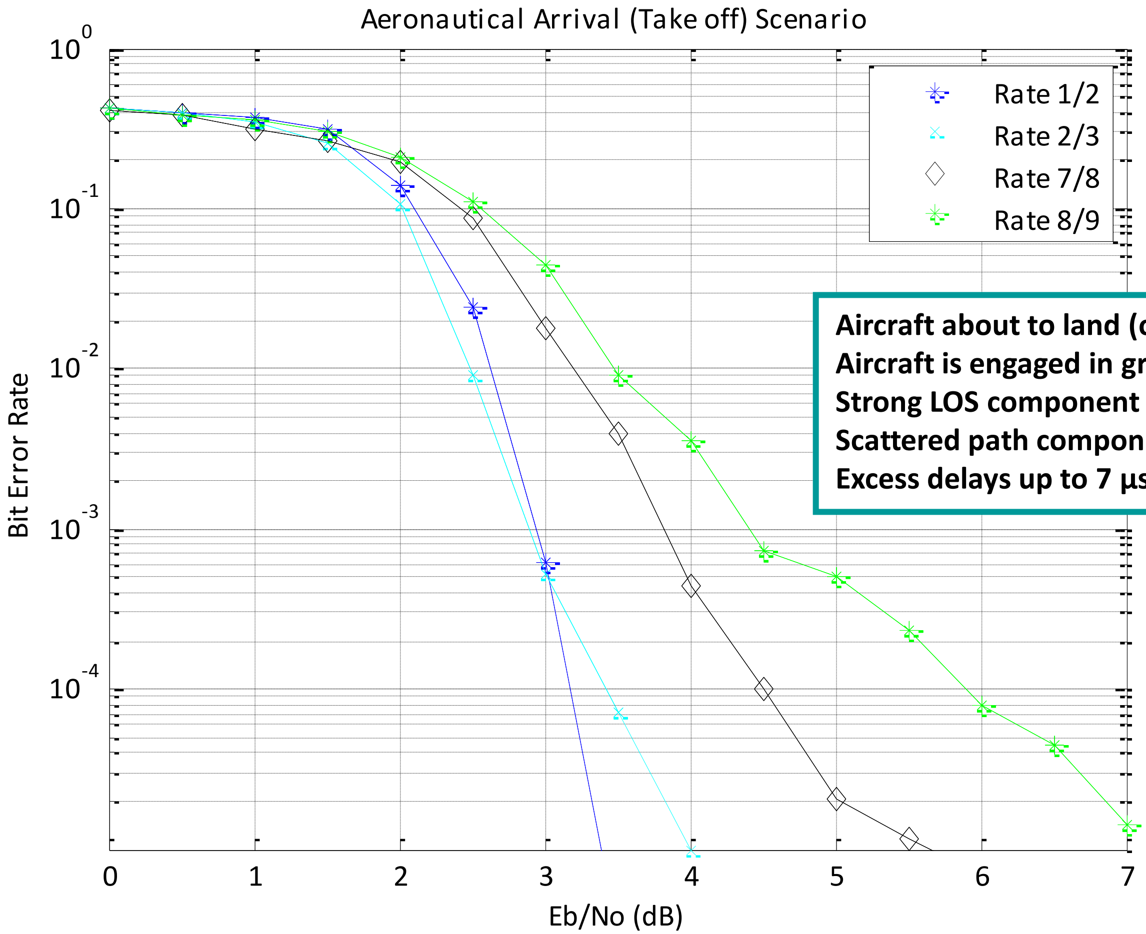
# Coded Performance in “AWGN”




| Coding Rate | Info. Bits ($\alpha$) | Coded Bits ($\beta$) |
|---|---|---|
| 1/2 | 1024 | 2048 |
| 2/3 | 1024 | 1536 |
| 7/8 | 1022 | 1168 |
| 8/9 | 1022 | 1152 |

**CPM-OFDMA-PCM-FM offers good coding gains over uncoded PCM-FM**
**Rate ½ coding offers ~ 6 dB gain over uncoded PCM-FM at BER of $10^{-5}$**
**Rate 8/9 coding offers ~ 2 dB gain over uncoded PCM-FM at BER of $10^{-5}$**

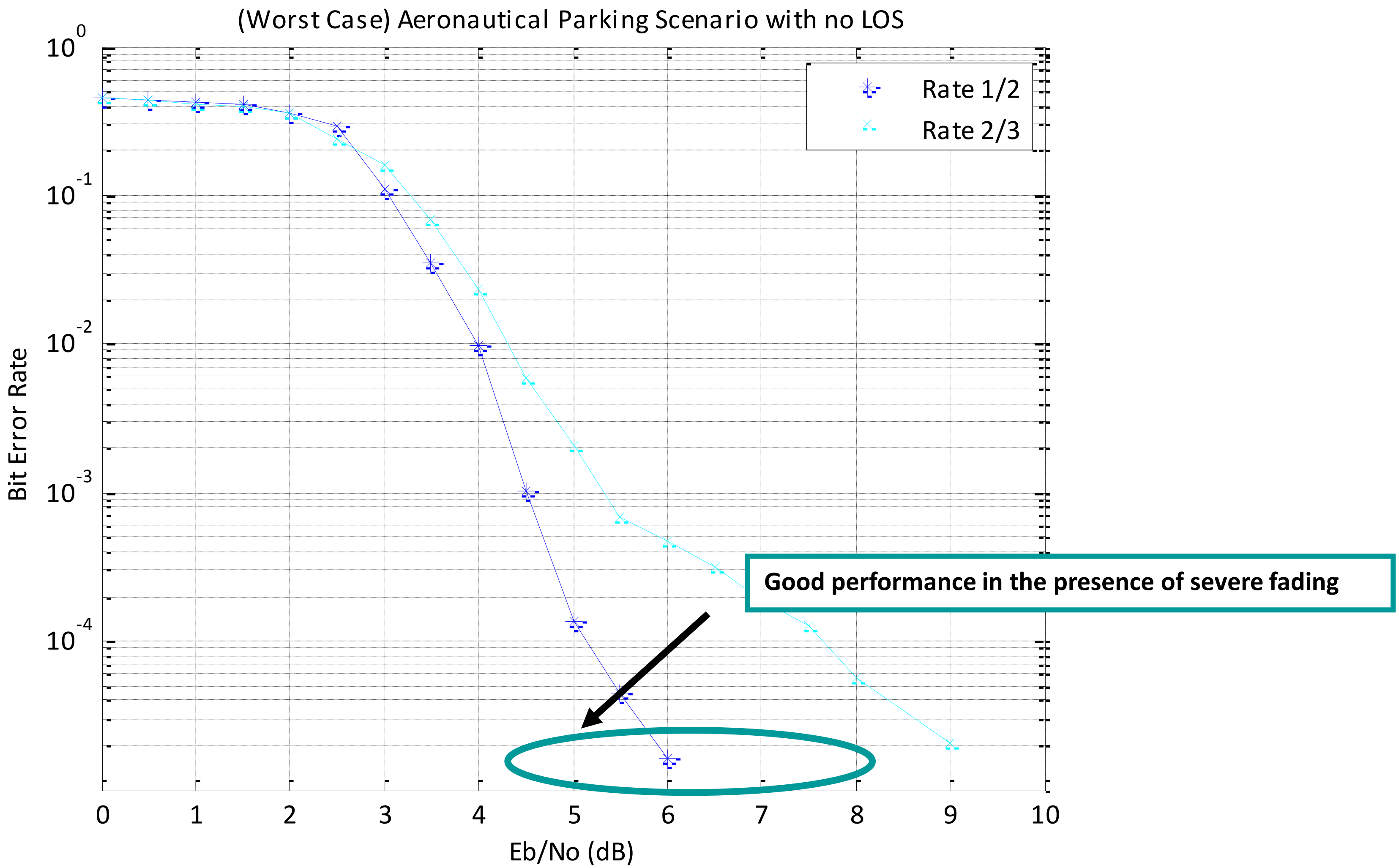
# “Take-Off” Channel




**Aircraft about to land (or take off)**
**Aircraft is engaged in ground-air communication**
**Strong LOS component is present (Krice = 15 dB)**
**Scattered path components from buildings**
**Excess delays up to 7 μs**

**Rate ½ code makes a SHARP transition at Eb/No > 3 dB**
**Rate 8/9 code achieves BER of $10^{-5}$ at lower Eb/No than is achieved by conventional PCM-FM in the AWGN channel**

# Parking Environment (No LOS)



# Conclusions

- CPM-OFDM(A) is a robust modulation that maintains much of the power efficiency of CPM + has the spectral efficiency of DFT pre-coded OFDMA
- Introduced SCCC CPM-OFDMA using PCM/FM as the kernel CPM modulation
- Showed that the most spectrally efficient (N = 1) implementation yields good performance in frequency selective fading radio channel environments
  - Rate ½ coding offers ~ 6 dB gain over uncoded PCM-FM at BER of 10-5
- Low complexity single-tap frequency domain equalization used with this CPM-like waveform offers advantage of use in frequency selective telemetry channel environments

# THANK YOU!

# QUESTIONS?