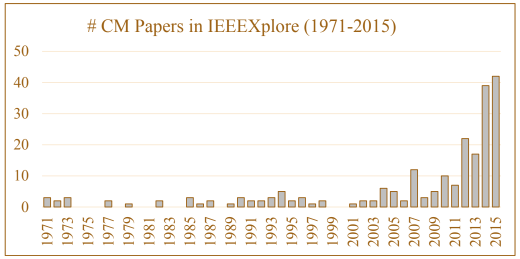
Systematic Antenna Design with Characteristic Modes

BUON KIONG LAU AND ZACHARY MIERS

Course Objective

- Theory of Characteristic Modes (TCM) proposed in 1971 by Garbacz and Harrington
- Time finally come for widespread interest
  - Research activities exploding



  - Major software vendors implemented characteristic mode analysis (CMA) due to strong customer interest

Course Objective

- This course designed to answer basic questions:
  - What is it? What's all the fuss about?
  - Can I use it in my work?
  - How do I get started?
  - How do I get involved?
  - What opportunities are there?
  - etc.
- This course to provide good foundation, NOT to treat fine details

Course Overview

Short, short course (2 hr)

- Course Objective
- Physical Insights
- Intro to CM Concepts
- Basic CM Analysis & Examples
- Specialized Example (Terminal antenna)
- Demo of CMA Tools
- Future Directions
- Concluding Remarks

Physical Insights of TCM

WHAT INSIGHTS, WHY ARE THEY USEFUL, HOW TO USE THEM?

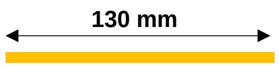
Physical Insights to Abstract Problems

- Electromagnetic systems are complex (Maxwell's Equations!)
- In many problems, object's resonance is important
- Energy stored also important:
  - Capacitive vs. inductive
- So are these issues:
  - Feed locations, radiation pattern, coupling, etc.
- TCM gives physical insights on these aspects

Acoustic resonance

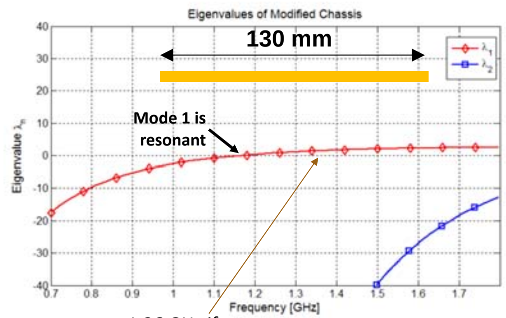
Physical Insights to Abstract Problems

- TCM for electromagnetic analysis and design
  - Provide inherent resonant properties of a structure
  - Depends only on geometry and materials
  - Useful to solve scattering and antenna problems
  - For antenna design, visualize possible radiation modes supported by structure
- Still too abstract? Let's demonstrate CMA using a dipole-like PEC structure (width of 4 mm)



Physical Insights with CMA

- How does a dipole antenna radiate?
  - Calculate CMs for the thin strip using eigenvalue decomposition
  - Eigenvalues indicate **resonance property**



Expect resonance at 1.36 GHz if 130mm is half a wavelength (λ/2)

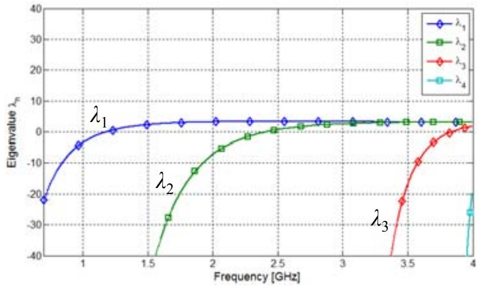
<u>Eigenvalues @750MHz</u>
Mode 1: -12
Mode 2: -1455
⋮

Physical Insights with CMA

- Multiple resonant frequencies
  - λ_1 is resonant at 1.2 GHz
  - λ_2 is resonant at 2.4 GHz, etc.

130 mm

- Excitation of Modes
  - Resonant modes
  - Non-resonant modes
    - ➢ Proper feed location(s)
    - ➢ Matching network
    - ➢ Structural change

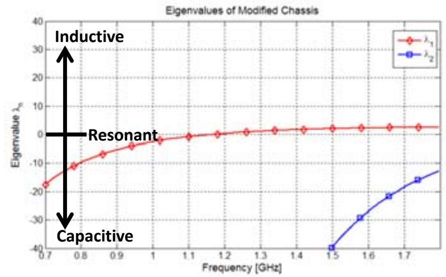


- Modes are orthogonal in currents and far-fields

Physical Insights with CMA

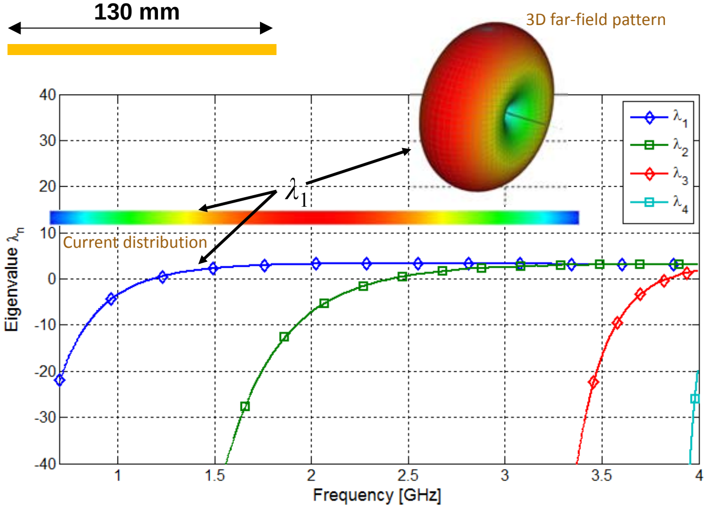
- "Capacitive" Mode, $\lambda_n < 0$
  - Stores electric energy W_e ($W_e > W_m$)
  - Often excited with capacitive coupling element
- "Inductive" Mode, $\lambda_n > 0$
  - Stores magnetic energy W_m ($W_m > W_e$),
  - Often excited with inductive coupling element

130 mm



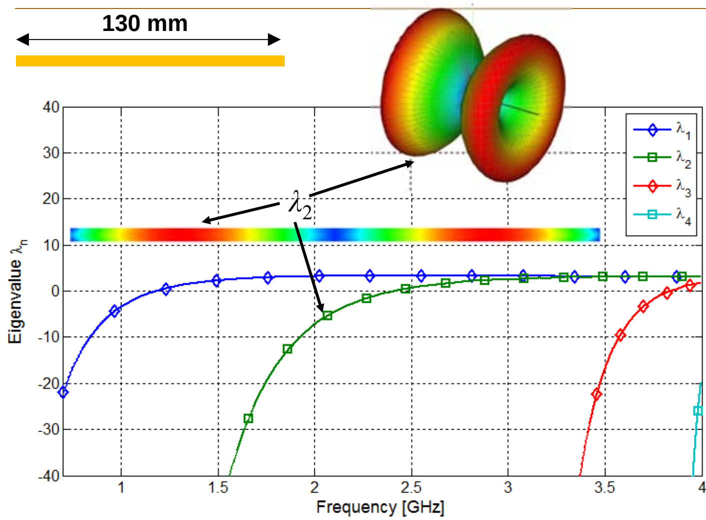
Modal Attributes of Thin Wire

130 mm

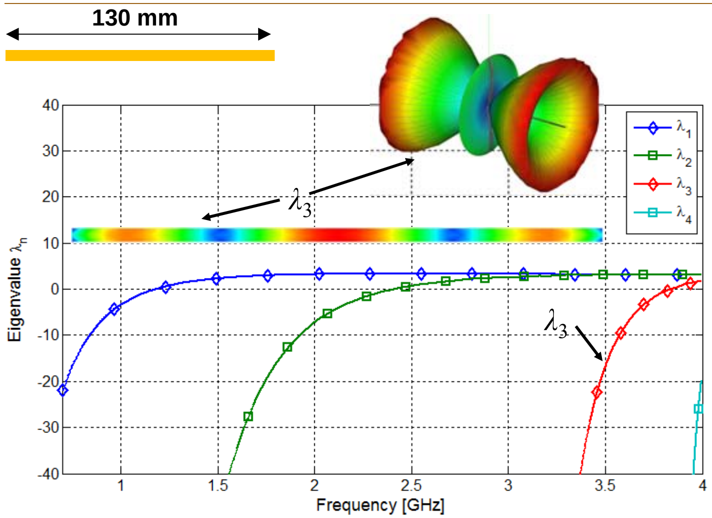


Modal Attributes of Thin Wire

130 mm



Modal Attributes of Thin Wire



Currents and Far-Fields Orthogonal

λ_1 – 

Standard $\lambda/2$ dipole pattern

Standard $\lambda/2$ dipole currents

λ_2 – 

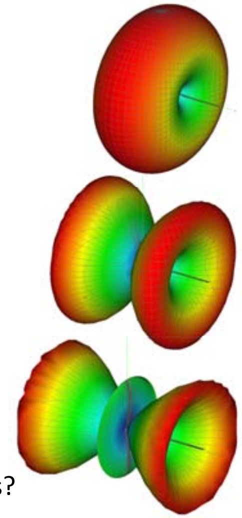
λ dipole pattern

λ dipole currents

λ_3 – 

$3\lambda/2$ dipole pattern

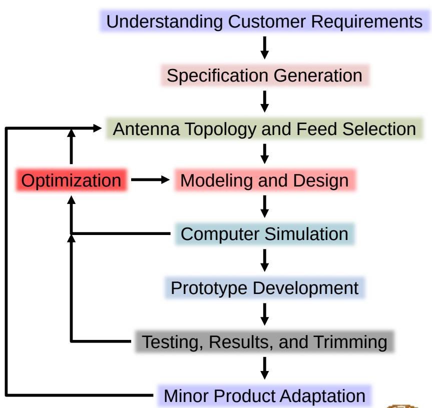
$3\lambda/2$ dipole currents



Question: Where to feed these modes?

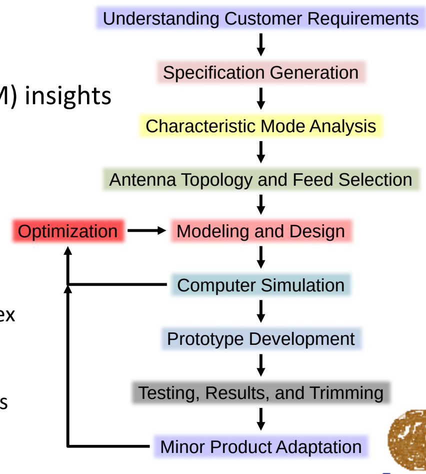
Current Integrated Antenna Design

- Start from an system
  - Not a closed form solution
- Complex
  - Multiple ideas
- Time consuming
  - Abstract ideas/information
- Optimization intensive
  - Computationally complex
- No physical insights



CM Integrated Antenna Design

- Start from an system
- Obtain electromagnetic (EM) insights
  - Resonant characteristics
- Utilize EM characteristics
  - Development of Feeds
- Traditional Optimization
  - Less computationally complex
- Full Understanding
  - Allows for future adaptations



Basic CM concepts

UNDERLYING THEORY, COMMON METRICS AND MODE TRACKING

Underlying Theory

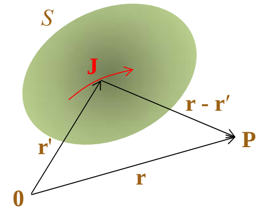
- Start from Electromagnetic Theory 101
- Current $\mathbf{J}(\mathbf{r}')$ on surface of conductor S causes electric field $\mathbf{E}(\mathbf{r})$ at point $\mathbf{r}$
- Solving Maxwell's Equations in time harmonic form, we obtain

$$\mathbf{E}(\mathbf{r}) = -\nabla\phi(\mathbf{J}) - j\omega\mathbf{A}(\mathbf{J})$$

where $\phi(\mathbf{J}) = -\frac{1}{j\omega\varepsilon}\oiint_S \nabla'\bullet\mathbf{J}(\mathbf{r}')\psi(\mathbf{r},\mathbf{r}')ds'$

$$\mathbf{A}(\mathbf{J}) = \mu\oiint_S \mathbf{J}(\mathbf{r}')\psi(\mathbf{r},\mathbf{r}')ds'$$

$$\psi(\mathbf{r},\mathbf{r}') = \frac{e^{-jk|\mathbf{r}-\mathbf{r}'|}}{4\pi|\mathbf{r}-\mathbf{r}'|}$$



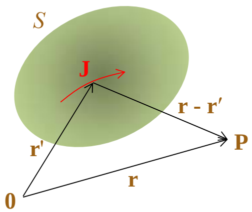
Underlying Theory

- But $\mathbf{J}(\mathbf{r}')$ is from an impressed field $\mathbf{E}^i(\mathbf{r}')$
  - antenna problem, known sources over S
  - scattering problem, known sources external to S (incident wave)
- Define operator $L(\mathbf{J}) = -\mathbf{E}(\mathbf{r})$, then at the conductor surface (boundary)

$$\left[L(\mathbf{J}) - \mathbf{E}^i(\mathbf{r})\right]_{\tan} = 0$$

Tangential component of induced E-field

- Define impedance operator $Z(\mathbf{J}) = \left[L(\mathbf{J})\right]_{\tan}, Z(\mathbf{J}) = R(\mathbf{J}) + jX(\mathbf{J})$
- To obtain CMs, perform generalized eigenvalue decomposition
  $Z(\mathbf{J}_n) = \nu_n W(\mathbf{J}_n)$
  where $W(\mathbf{J}_n)$ is the weight operator



Underlying Theory

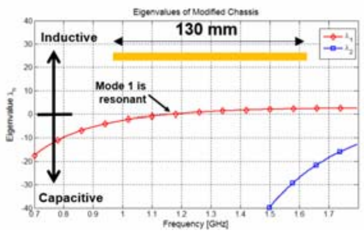
- Eigenfunctions $\mathbf{J}_n$ are real-valued since $Z(\mathbf{J})$ is symmetric operator
- $\mathbf{J}_n$ orthogonal by default, free to choose $W(\mathbf{J}_n)$
- Radiated power (of mode n) given by

$$P_n = \left\langle \mathbf{J}_n^*, R(\mathbf{J}_n)\right\rangle = \oiint_S \mathbf{J}_n^*\bullet R(\mathbf{J}_n)ds$$

- To obtain orthogonal far-fields for the modes, let $W(\mathbf{J}_n) = R(\mathbf{J}_n)$

$\Rightarrow X(\mathbf{J}_n) = \lambda_n R(\mathbf{J}_n), \nu_n = 1 + j\lambda_n$ (CM eigenvalue equation)

- Eigenvalue λ_n relates to difference in stored energies ($W_\mathrm{m} - W_\mathrm{e}$):
  - $W_\mathrm{m} > W_\mathrm{e}$ (inductive)
  - $W_\mathrm{e} > W_\mathrm{m}$ (capacitive)



Underlying Theory

- For computation, operator $Z(\mathbf{J})$ is discretized over surface S as impedance matrix $\mathbf{Z} = \mathbf{R} + j\mathbf{X}$ using method-of-moments (MoM)
- $\mathbf{J}(\mathbf{r}')$ becomes scalar current vector $\mathbf{I}$ associated with $\mathbf{Z}$
- Therefore, eigenvalue equation becomes

$$\mathbf{X}\mathbf{I}_n = \lambda_n \mathbf{R}\mathbf{I}_n$$

- Characteristic currents should be normalized such that radiated power is 1 for all modes:

$$\mathbf{I}_n^H \mathbf{R}\mathbf{I}_n = \mathbf{I}_n^T \mathbf{R}\mathbf{I}_n = 1$$

CM Metric: Modal Significance

- Recall that $\left[L(\mathbf{J}) - \mathbf{E}^i\right]_{\tan} = 0$ and all currents can be written as $\mathbf{J} = \sum_n a_n \mathbf{J}_n$
- Taking inner product with $\mathbf{J}_m$: $\sum_n a_n \langle \mathbf{J}_m, \mathbf{Z}\mathbf{J}_n \rangle = \underbrace{\left\langle \mathbf{J}_m, \left[\mathbf{E}^i\right]_{\tan} \right\rangle}_{\text{modal excitation coefficient}}$
- Using properties of CM,

$$a_n(1 + j\lambda_n) = \left\langle \mathbf{J}_n, \left[\mathbf{E}^i\right]_{\tan} \right\rangle \Rightarrow a_n = \frac{\left\langle \mathbf{J}_n, \left[\mathbf{E}^i\right]_{\tan} \right\rangle}{1 + j\lambda_n}$$

- Modal significance (MS) is defined as:

$$MS = \left| \frac{1}{(1 + j\lambda_n)} \right|$$

(normalization for the characteristic current $\mathbf{J}_n$)

CM Metric: Modal Bandwidth

- Bandwidth defined as:

$$BW = \frac{f_h(S_{11} = \gamma) - f_l(S_{11} = \gamma)}{f_c}, \text{typically } \gamma = -6 \text{ or } -10\text{dB}$$

- Modal Significance can be used to define "bandwidth":

$$BW = \frac{f_H\left(MS = 1/\sqrt{2}\right) - f_L\left(MS = 1/\sqrt{2}\right)}{f_c(MS = 1)}$$

- This was determined useful as it matches the modal Q

$$Q \approx \frac{1}{BW}$$

(Note: This does not relate well to excitable bandwidth)

CM Metric: Characteristic Angle

- $\mathbf{J}_n$ is the orthogonal set of currents induced by $\mathbf{E}^i$
- $\mathbf{J}_n$ releases the energy accepted from $\mathbf{E}^i$ as $[\mathbf{E}_n]_{\tan}$
- $[\mathbf{E}_n]_{\tan}$ has an associated characteristic angle ("scattered" phase) α_n
- If no time lag, mode n acts like perfect scatterer, i.e. 180° shift
- Inductive modes store magnetic energy for a period of time
  - Time lag of magnetic energy, i.e. $90° < \alpha_n < 180°$
- Capacitive modes store electric energy for a period of time
  - Time lag of electric energy, i.e. $180° < \alpha_n < 270°$
- Characteristic angle is defined by:

$$\alpha_n = 180° - \tan^{-1}(\lambda_n)$$

e.g. Insight into Yagi-Uda antenna

Characteristic Mode Tracking

- Eigenvalues found by solving the equation (discrete form):

$$\mathbf{X}\mathbf{I}_n = \lambda_n \mathbf{R}\mathbf{I}_n$$

- Solution is frequency dependent
  - Every frequency has a different impedance matrix
  - At every frequency λ_n is found in a different order
- Eigenvalues are not sorted between frequencies
  - Eigenvalue tracking algorithms needed
- Orthogonal properties not guaranteed across frequency

Z. Miers and B. K. Lau, "Wide band characteristic mode tracking utilizing far-field patterns," *IEEE Antennas Wireless Propag. Lett.*, vol. 14, pp. 1658-1661, 2015.

E. Safin and D. Manteuffel, "Advanced eigenvalue tracking of characteristic modes," *IEEE Trans. Antennas Propag.*, in press. (Special Issue on Theory and Applications of Characteristic Modes)

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Eigenvector Correlation Tracking

- Eigenvector correlation based on

$$\rho_{m,n} = \frac{\mathbf{I}_m^H \mathbf{I}_n}{|\mathbf{I}_m||\mathbf{I}_n|}$$

  - Easy to implement
  - Widely implemented
- Based on orthogonal currents assumption
  - not rigorous since actually $\mathbf{I}_m^H \mathbf{R}\mathbf{I}_n = \mathbf{I}_m^T \mathbf{R}\mathbf{I}_n = 0,\ m \neq n$
  - Structure discretized, sensitive to errors
  - Orthogonality of currents not guaranteed across frequency

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Surface Current Correlation Tracking

- Correlation of "surface current" (or "radiated power")

$$\rho_{m,n} = \left\langle \mathbf{J}_m, \mathbf{R}\left(\mathbf{J}_n\right)\right\rangle = \mathbf{I}_m^H \mathbf{R}\mathbf{I}_n$$

- For a given frequency: $\mathbf{I}_m^H \mathbf{R}\mathbf{I}_n = \mathbf{I}_m^T \mathbf{R}\mathbf{I}_n = 0,\ m \neq n$
- Total surface current is "more orthogonal"
  - $\mathbf{R}\left(\mathbf{J}_n\right)$ does not vary quickly in frequency
  - Uses more characteristic information of structure
  - Usually better than eigenvector correlation
    - » Currents of individual discretized elements can vary more across frequency
  - Easy to implement

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Hybrid Tracking

- Utilizes a mixture of different algorithms
  - Traditionally with mixed linear correlation functions
  - Tracking of eigenvalues using image processing techniques
  - Can utilize any other form of tracking
- Only as good as the algorithms used
  - Easy or hard to implement
  - Can be computationally efficient if used wisely

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Far-Field Tracking

- Correlation of far-field pattern data

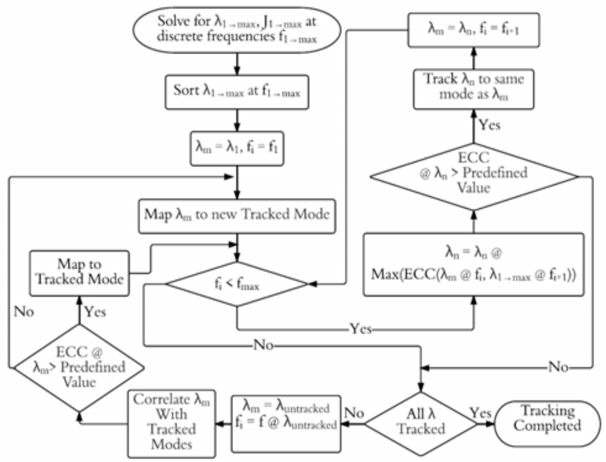
$$\rho_{m,n}^{CM} \approx \frac{\left| \oint_{4\pi} \left[E_{\phi,n}(\Omega) E_{\phi,m}^{*}(\Omega) + E_{\theta,n}(\Omega) E_{\theta,m}^{*}(\Omega) \right] d\Omega \right|^2}{\left| \oint_{4\pi} G_n(\Omega) d\Omega \right| \left| \oint_{4\pi} G_m(\Omega) d\Omega \right|}$$

where

$$G_i(\Omega) = |E_{\phi,i}(\Omega)|^2 + |E_{\theta,i}(\Omega)|^2 \qquad d\Omega = sin\theta d\phi d\theta = (\phi, \theta)$$

  - Discretized data is orthogonal for same frequency
  - Fields not always orthogonal across frequency, but more stable than currents
  - Computationally more complex (need far-fields)
  - Struggles with degenerated modes

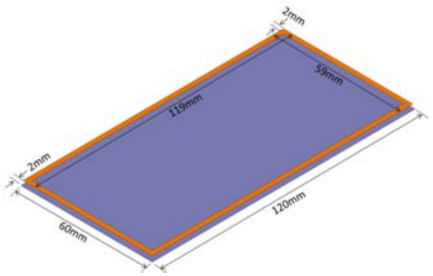
Lund University Tracking Method



Z. Miers and B. K. Lau, "Wide band characteristic mode tracking utilizing far-field patterns," *IEEE Antennas Wireless Propag. Lett.*, vol. 14, pp. 1658-1661, 2015.

Comparison of Tracking Methods

- Flat PEC chassis 60 mm × 120 mm, 2 mm wide rectangular metal ring 2 mm above the ground plane
- There exist modes with differences limited to high currents in small regions of the structure



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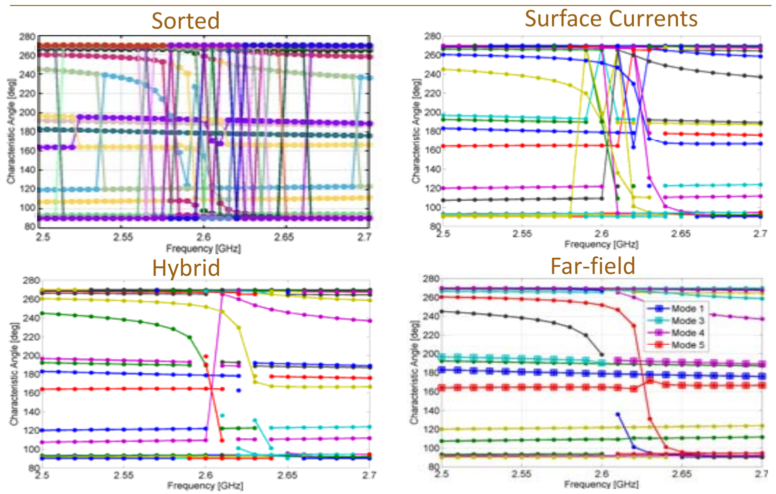
Comparison of Tracking Methods



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Basic CM Analysis

EIGENVALUES, CURRENTS, NEAR-FIELDS, AND FAR-FIELDS

Antenna Analysis – Eigenvalues

- Eigenvalues provide a "quick look" of antenna properties
  - Where are the resonances
  - How many modes can be excited by antenna(s)
- Further physical insights from quality factor Q
  - Approximate calculation is quick and easy (Q ≈ 1/bandwidth)
    - » Modal significance → modal bandwidth
    - » slope of eigenvalue $d\lambda_n / d\omega$ → obtainable bandwidth
  - Can modal bandwidth meet the requirements?
- Characteristic angle for analyzing reflection of a mode

Antenna Analysis – Currents

- Insights into structural modifications
  - Areas of high current will impact the eigenmode
  - Areas of low current will have less impact on eigenmode
- Insights into current[1] and voltage feeds
  - Splitting structures in areas of high current
  - Impact of feed location on multi-mode excitation
- Correlation functions allow for other additional insights
  - For example, comparison of structures, feed locations, etc.

[1] Current feeds can only be implemented through voltage induced currents

Antenna Analysis – Near-fields

- 3D structural changes
  - Information beyond physical structure allowing insights into structural changes
- Feed analysis of "complete units"
  - Capacitive coupling elements
  - Inductive coupling elements
- Coupling analysis
  - Feeds, matching circuits, and element modifications
  - Impact of multiple feeds
- Correlation functions allow for other additional insights

Antenna Analysis – Far-fields

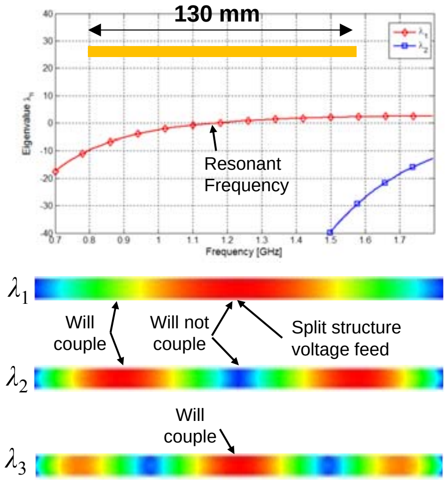
- Provides structure-to-structure analysis
  - Structural modifications
    - » Modal changes across structure adaptations
    - » Allows for specific mode optimization

Examples of CM Analysis

DIPOLE, WIDEBAND DIPOLE, SPIRAL

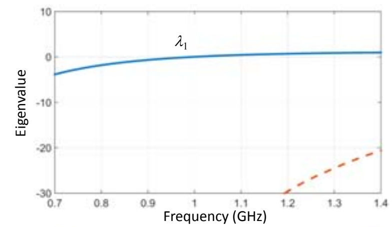
Thin Wire - Dipole Antenna

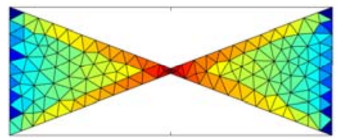
- Eigenvalue analysis
  - Resonance → 1.15GHz
  - BW → 14%
- Currents analysis
  - Center feed with splitting
  - Will not couple to λ_2
  - Will couple to λ_3



Bow-Tie Antenna

- Eigenvalue analysis
  - Resonance → 1.0GHz
  - BW → 26%
  - “single mode” contribution
- Currents analysis
  - Center fed with splitting
  - Constant over frequency
- Near-field analysis
  - Shift significantly over frequency



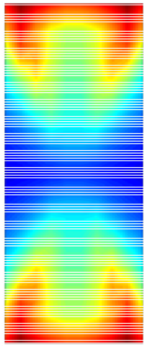


Current distribution along bow-tie for λ_1

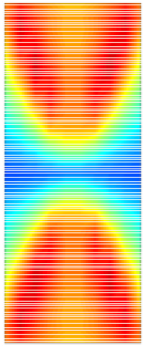
Bow-Tie (Characteristic Near-fields)

- Near-field analysis (10 mm above bow-tie)

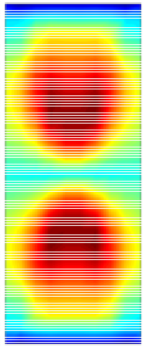
λ_1
Electric Field
700 MHz



λ_1
Electric Field
1.30 GHz



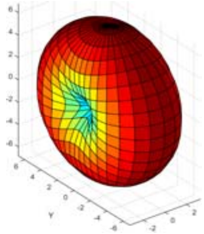
λ_1
Electric Field
Un-corrilated



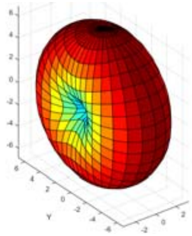
Bow-Tie Eigen Patterns vs FEM Simulation

- Far-field analysis

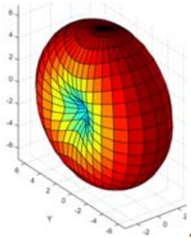
λ_1 at 850 MHz
99% FEM
-6dB match



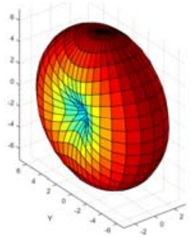
λ_1 at 1.05 GHz
97% FEM
-12dB match



λ_1 at 950 MHz
97% FEM
-14dB match



λ_1 at 1.15 GHz
89% FEM
-6dB match

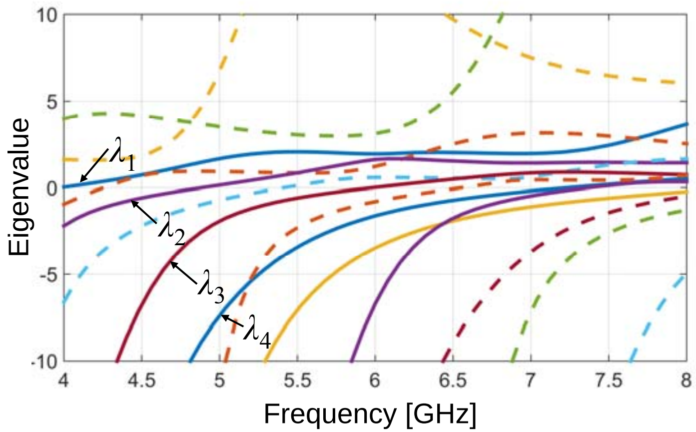


Logarithmic Spiral Antenna

- Wideband antennas can be better understood
  - Analysis of orthogonal currents
  - Modal "hopping" becomes obvious
  - Far-field modal contribution
  - CMA vs excited structures

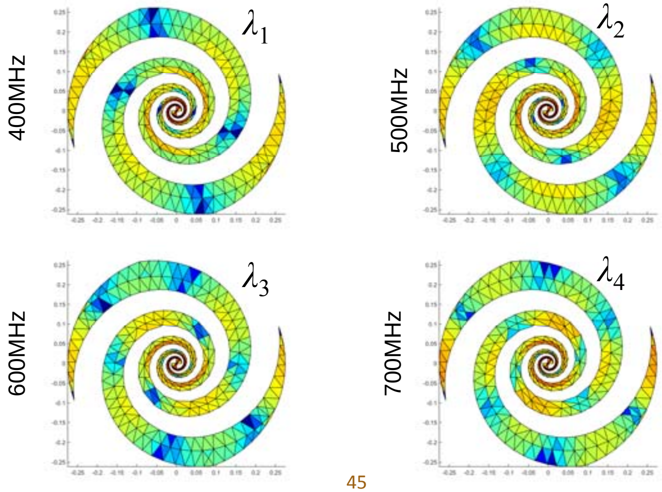
Single Eigenmode Contribution

- Solid lines contribute to >80% of "typical pattern" across resonance



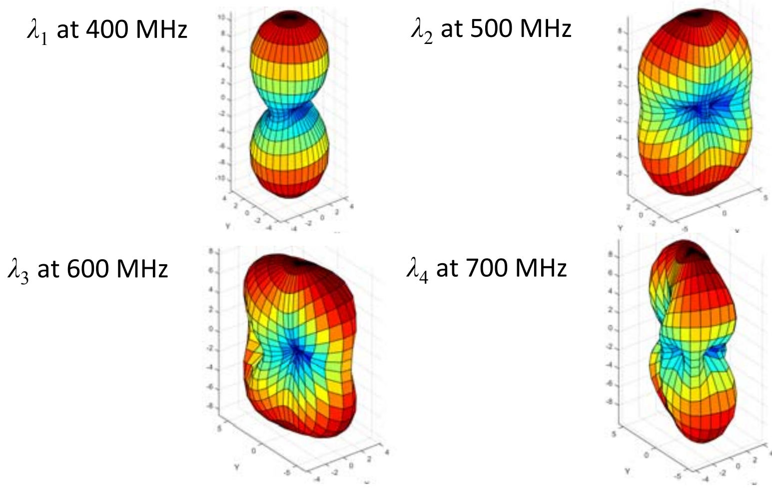
Current Distribution of Dominant CM

- Single excitation of specific modes observed



Pattern Variation Across Frequency

- Different modes over frequency, pattern evolving/rotating

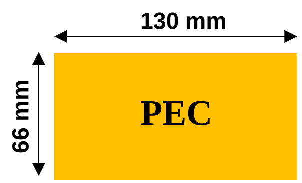


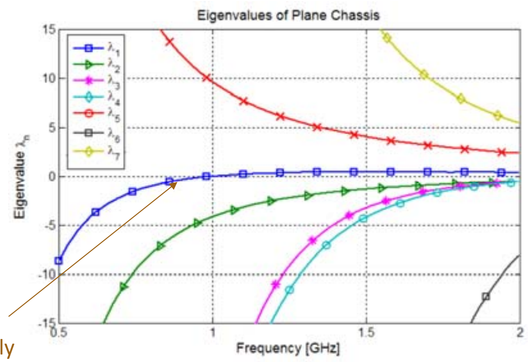
TCM-Assisted Terminal Design

STANDARD FLAT CHASSIS, COMPONENT CHASSIS

TCM for Terminal Antennas

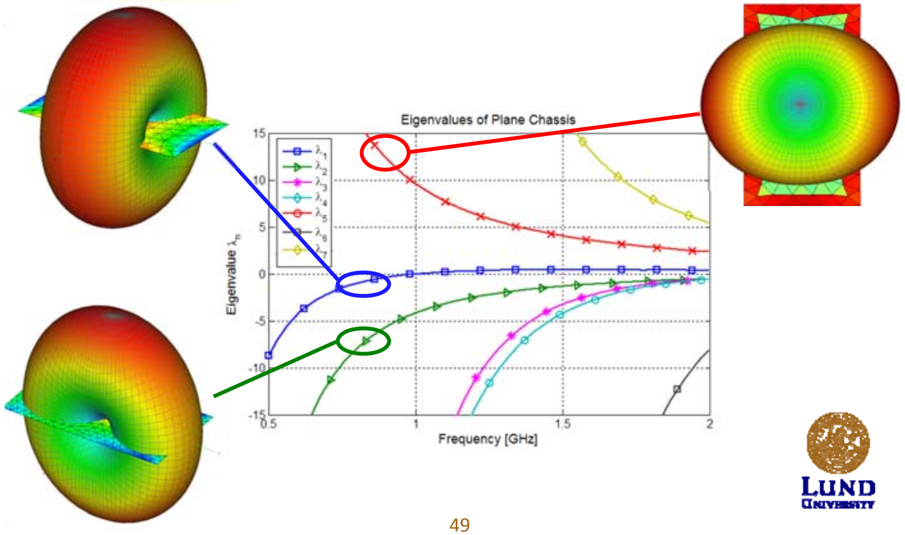
- Consider 130 mm × 66 mm chassis of a "typical mobile"
- What modes are available, can they be adapted?





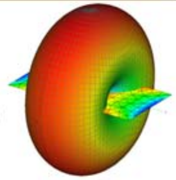
Goal: Design multi-antennas for MIMO application (< 1 GHz), only 1 resonant mode, possible?

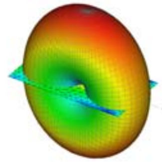
CMA for Structure Alteration

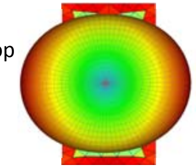


Mode adaptation (850 MHz)

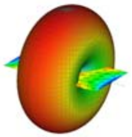
- Mode 1 (λ_1)
  - Currents alternating along the length of the chassis
  - Modal pattern represents that of a dipole along length
  - Slightly capacitive, near resonance
- Mode 2 (λ_2)
  - Currents alternating along the width of the chassis
  - Modal pattern represents that of a dipole along width
  - Very capacitive, not near resonance
- Mode 3 (λ_3)
  - Currents rotating around structure
  - Modal pattern represents that of a resonant loop
  - Very inductive, not near resonance



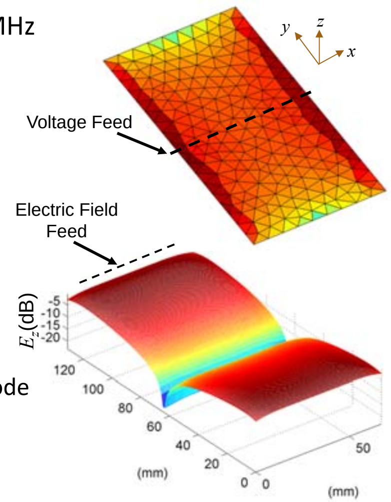




CMA of Mode 1

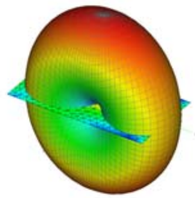


- Mode 1 is near resonance at 850 MHz
- Splitting of the chassis
  - Not often allowed
- Utilization of near-field feeding
  - Many typical antennas
  - Top loading of structure
  - Matching Circuits
- Not an interesting mode
  - Well-known and often utilized mode
  - Modal features used in MIMO



CMA of Mode 2

- Mode 2 is not resonant < 2 GHz
  - Must use structural adaptation
- Sectioning or splitting the chassis
  - Not often allowed, may not help
- Utilization of near-field Feeding
  - Must be near resonance for usefulness
  - Side loading of structure
  - Matching circuits do not help with excitation
- Very interesting mode for CMA
  - Modal features used in MIMO



CMA of Mode 2

- Modal Currents
  - Resemble that of dipole along width
  - Far-field verifies this assumption
- Closed form dipole modifications can now be used
  - Capacitive loading
  - Inductive loading
- Top-hat (capactive) loading method chosen

H. Li, Z. Miers, and B. K. Lau, "Design of orthogonal MIMO handset antennas based on characteristic mode manipulation at frequency bands below 1 GHz," *IEEE Trans. Antennas Propag.*, vol. 62, no. 5, pp. 2756-2766, May 2014.

Z. Miers, H. Li, and B. K. Lau, "Design of bandwidth enhanced and multiband MIMO antennas using characteristic modes," *IEEE Antennas Wireless Propag. Lett.*, vol. 12, pp. 1696-1699, 2013. (Special Cluster on Terminal Antenna Systems for 4G and Beyond)

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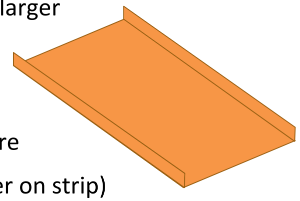
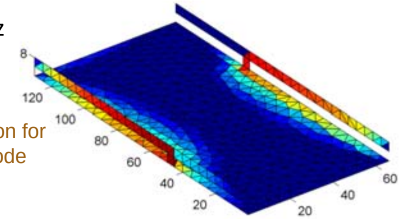
Mode 2 Modification

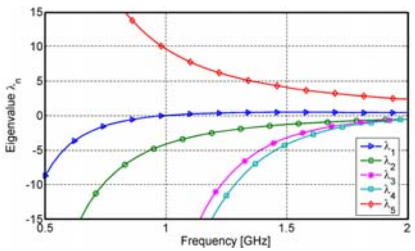
- Add top-hat type features to the chassis (shorted along length of structure – physically bigger and adds capacitance)
  - Forces currents to outer edge, electrically larger
  - Pushes resonance to 1.6 GHz
- Add structural series inductance
  - Forces currents through section of structure
  - Increases outer capacitance (voltage higher on strip)
  - Pushes resonance to below 1 GHz

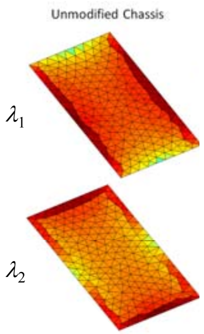




Current distribution for low frequency mode

Resonant Mode 2, and New Mode



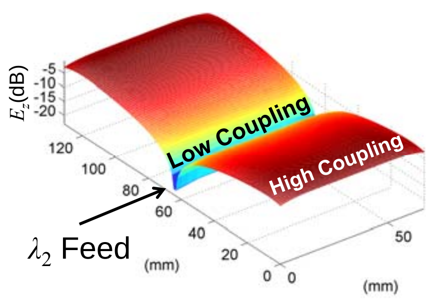


Characteristic current distributions at 0.8 GHz

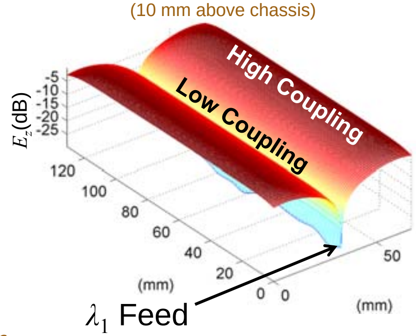
Feeding Analysis

- MIMO antenna feeding considerations
  - Low coupling required
  - Multiple antennas, multiple feeds

Near field of λ_1
(10 mm above chassis)



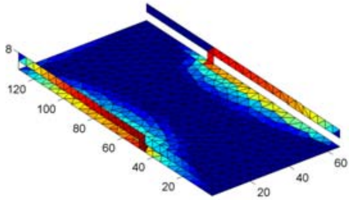
Near field of λ_2
(10 mm above chassis)



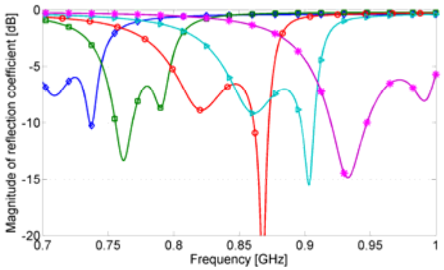
Physical Understanding – Easy Adaptation

- Mode resonances is based on:
  - Total capacitance
  - Location of inductance (shorting strip)
  - Amount of inductance (width of shorting strip)

Current distribution for low frequency mode



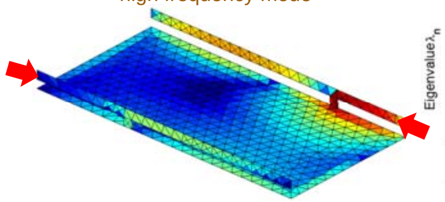
Effect of moving shorting strip position

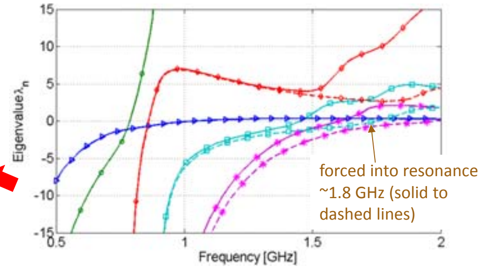


Modal Tracking – Multiband Response

- High frequency resonances:
  - Tracking modes across frequency
  - Modal correlation in feed areas
  - Apply modal analysis on high frequency mode (force into resonance at desired frequency)

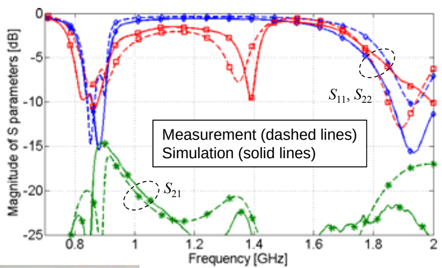
Current distribution for high frequency mode

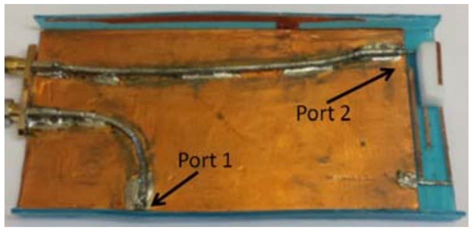




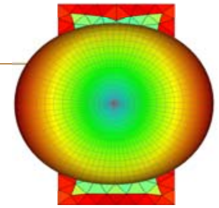
From TCM to Full Prototype

- TCM Design
- CST Model
  - Dielectrics
  - Feed matching
- Prototype

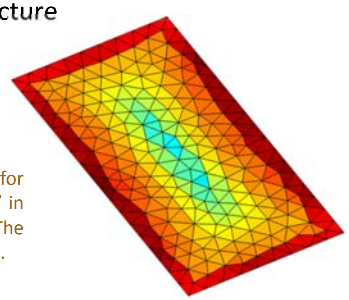




CMA of Mode 3



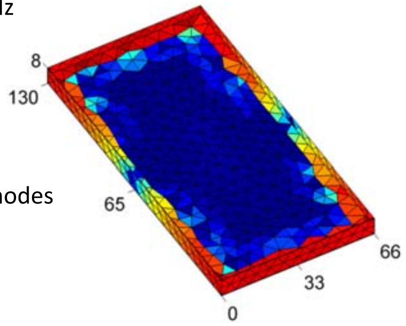
- Modal Currents
  - Resemble that of resonant loop
  - Far-field verifies this assumption
- Closed form loop modifications can now be used
  - Inline loops, not possible with structure
  - Secondary loop
- Apply and test theory



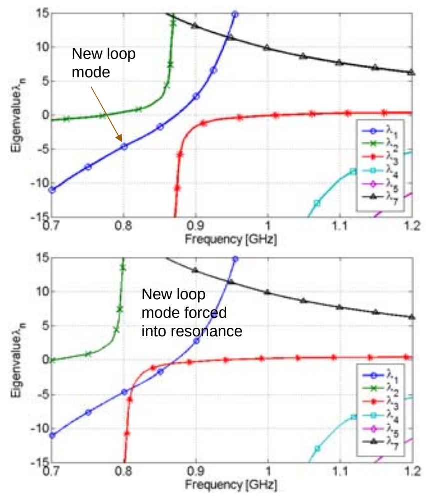
Z. Miers, H. Li, and B. K. Lau, "Design of bezel antennas for multiband MIMO terminals using characteristic modes," in *Proc. 8th Europ. Conf. Antennas Propag. (EuCAP'2014)*, The Hague, The Netherlands, Apr. 6-10, 2014, pp. 2556-2560.

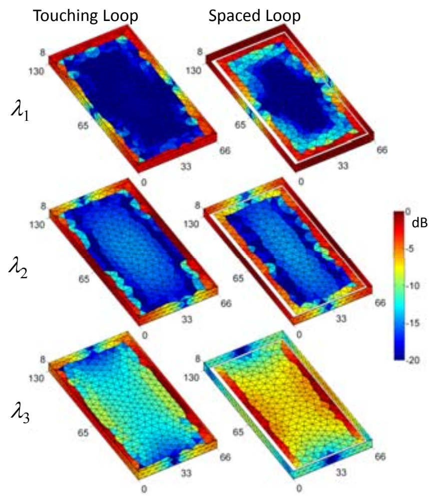
Mode 3 Modification

- Add secondary loop features to the structure
  - Forces currents to outer edge, electrically larger
  - Pushes resonance to below 1 GHz
- Impacts fundamental mode
  - Forces only single resonances
  - Isolation of the loop
  - Allows for tuning and multiple modes



Dual Low Band Resonance (Bezel)

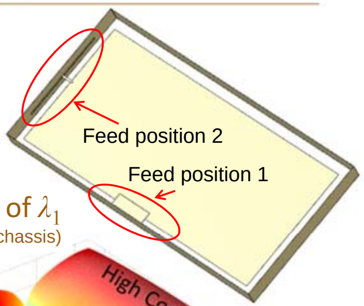




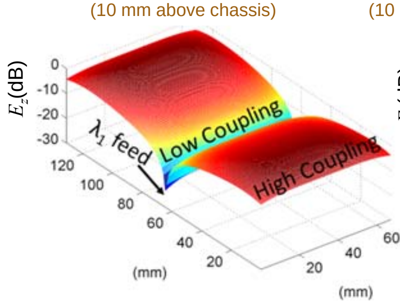
Characteristic current distributions at 0.8 GHz

Utilize TCM for Feeding

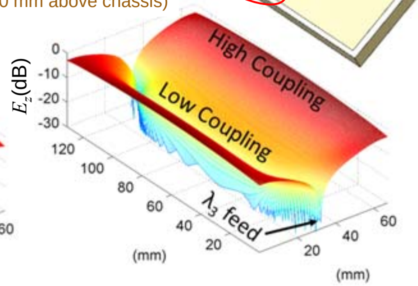
- Low coupling areas
  - Low feed coupling
- High coupling areas
  - High feed coupling



Near field of λ_3
(10 mm above chassis)

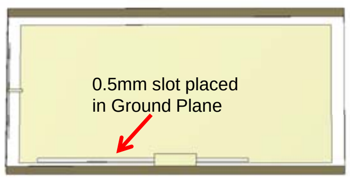


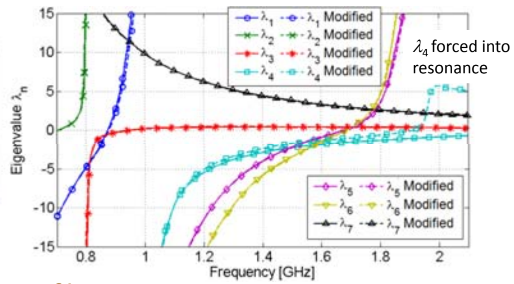
Near field of λ_1
(10 mm above chassis)



Modal Tracking

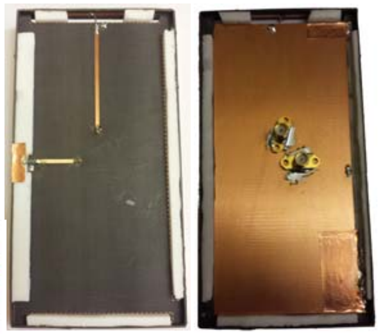
- High frequency resonances:
  - Shows how feeds can excite higher order modes
  - Apply modal analysis on high frequency mode
  - Application of slot forces mode into resonance

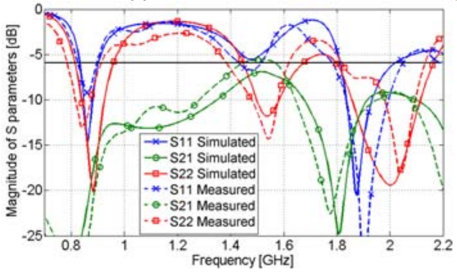




From TCM to Full Prototype

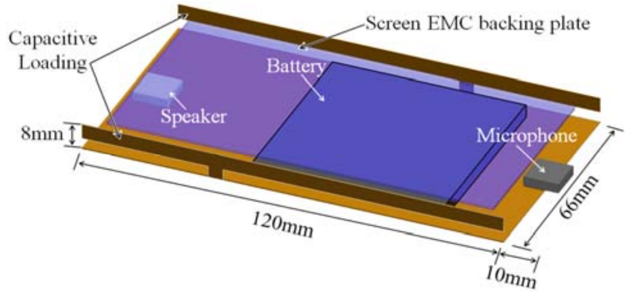
- TCM Design
- CST Model
  - Dielectrics
  - Feed matching
- Prototype





Full Structure TCM

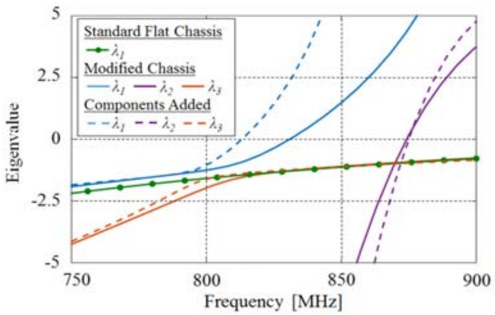
- How practical is TCM design approach? Will it still work with components integrated?
- Consider a "fully-equipped" mobile terminal



Z. Miers, A. Sekyere, J. A. Enohnyaket, M. Landaeus, and B. K. Lau, "Effects of internal components on designing MIMO terminal antennas using characteristic modes," in *Proc. 10th Europ. Conf. Antennas Propag. (EuCAP'2016)*, Davos, Switzerland, Apr. 10-15, 2016.

TCM Design with Impact of Components

Impact of components on CM eigenvalues



- Design approach identical to that of previous examples
  - Analyze modal currents
  - Utilize antenna theory for basic adaptation (capacitive/inductive loading)
  - Utilize structural loading to create or modify modes

Quick Demo of CMA Software

MATLAB-BASED, FEKO, CST, WIPL-D

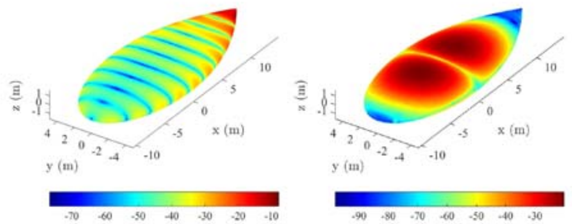
Future Directions & Conclusions

REFINING THEORY AND NEW APPLICATIONS

Electrically Larger Problems

- Current emphasis on structures around 1λ
- Complex for larger structures: Numerical issues and many resonant modes
- Attracting more interest (W. C. Chew, UIUC, USA; WIPL-D)

Q. Dai, et al. "Large-scale characteristic mode analysis with fast multipole algorithms," *IEEE Trans. Antennas Propag.*, in press. (Special Issue on Theory and Applications of Characteristic Modes)



Eigencurrents (dB) for two modes of "NASA almond" structure (up to 5λ)

TCM for Dielectric/Magnetic Materials

- Motivation: CM analysis and design for problems with non-PEC materials:
  - dielectric resonators/loading, body-worn antennas, etc.
- Basic theory exists from 1970's, but incomplete:

R. F. Harrington, J. R. Mautz, and Y. Chang, "Characteristic modes for dielectric and magnetic bodies," *IEEE Trans. Antennas Propag.*, vol. 20, no. 2, pp. 194-198, Mar. 1972.

Y. Chang and R. F. Harrington, "A surface formulation for characteristic modes of material bodies," *IEEE Trans. Antennas Propag.*, vol. 25, no. 6, pp. 789-795, Nov. 1977.

  - Eigenvalue no longer give resonance
  - Existing integral formulations complex (volume-based) or have internal resonances (surface-based)

TCM for Dielectric/Magnetic Materials

- Two research tracks:
  - New surface-based formulations to address shortcomings (Y. Chen, UESTC, China; C. F. Wang, NUS, Singapore)

    Y. Chen, "Alternative surface integral equation-based characteristic mode analysis of dielectric resonator antennas," *IET Microw. Antennas Propag.*, vol. 10, no. 2, pp. 193-201, 2016

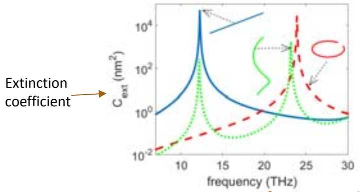
  - Removing internal resonances in surface formulations (Z. Miers/B. K. Lau, LU, Sweden; McNamara, Uni Ottawa, Canada)

    Z. Miers and B. K. Lau, "Computational analysis and verifications of characteristic modes in real materials," *IEEE Trans. Antennas Propag.*, in press. (Special Issue on Theory and Applications of Characteristic Modes)

- More research needed!

Examples of New Applications

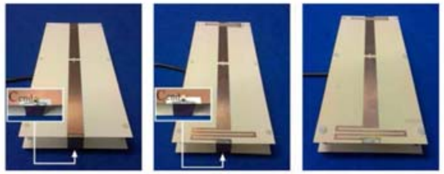
- Non-destructive testing of carbon nanotubes (CNT)



Scattering property for 3 CNT shapes

A. M. Hassan, et al., "Electromagnetic resonances of individual single-walled carbon nanotubes with realistic shapes: A characteristic modes approach," *IEEE Trans. Antennas Propag.*, in press. (Special Issue on Theory and Applications of Characteristic Modes)

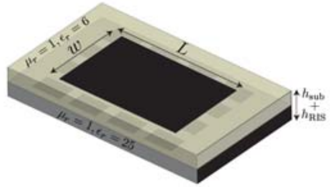
- Design of radiative RF coil for ultrahigh-field (UHF) MRI

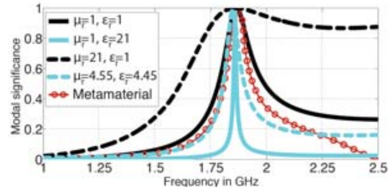

Analysis of coupling mechanism for different designs

Z. Chen, et al., "Coupling Investigation of different RF coil elements for 7-Tesla Magnetic Resonance Imaging based on characteristic mode analysis" in *Proc. IEEE MTT-S Int. Microw. Symp.*, Tampa, FL, Jun. 1-6, 2014

Examples of New Applications

- Analysis of metamaterial structures


Patch antenna over reactive impedance surface (RIS)



Modal significance of mode 1 for different substrates

M. H. Rabbah, et al., "Analysis of miniature metamaterial and magneto-dielectric arbitrary-shaped patch antennas using characteristic modes: Evaluation of the Q factor" *IEEE Trans. Antennas Propag.*, in press. (Special Issue on Theory and Applications of Characteristic Modes)

Concluding Remarks

- TCM gives valuable physical insights into antenna and scattering problems, systematic design/analysis possible!
- Critical mass in applying TCM is reached!
- Basics of TCM and CMA explained
- Analysis and design demonstrated for common/specialized cases
- Proposed **action points** for all of you:
  - Get started: You will received Makarov-script based TCM software by email within a week (Note: use as is, no user support!), etc. Full video introduction to be made available
  - Get involved: Join the TCM community (Special Interest Group on TCM, see characteristicmodes.org for more information)
  - Find your niche, still many stones left unturned
  - Have fun!