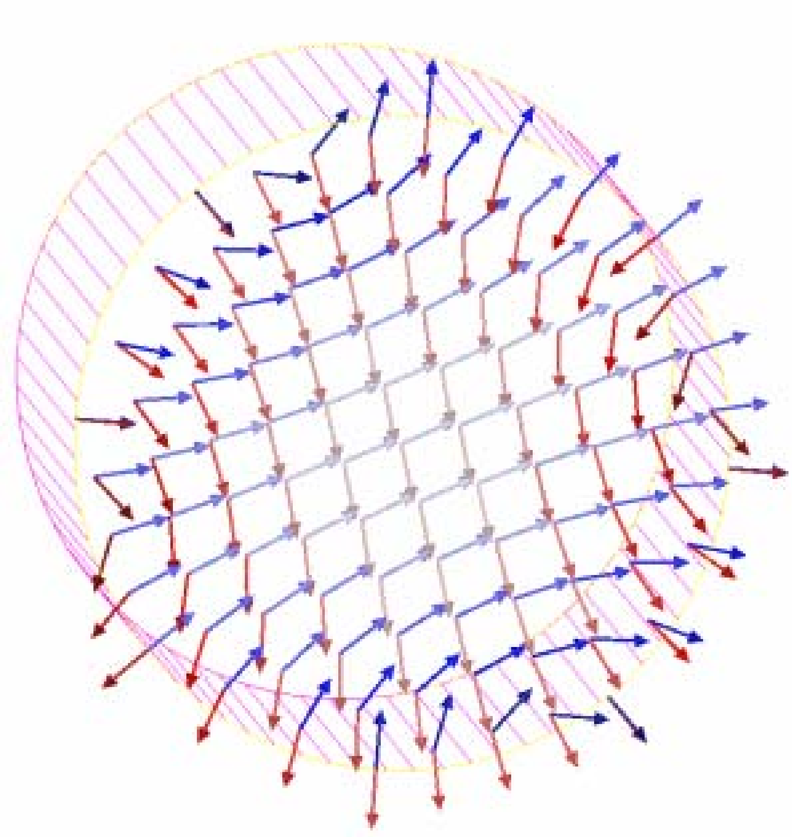
- This presentation is one in a series of Port Tutorials, intended to help users better understand the nuances of model excitation. With incorrect inputs, the entire 3D field solution will be incorrect. Therefore, proper attention to port definitions can make the difference between a successful and unsuccessful HFSS analysis.
- In this tutorial presentation, the user will be presented with guidelines for selecting between the use of Wave and Lumped port mechanizations, based on the port location in the model volume, separation from other ports, and the need for multiple terminal excitation outputs. Pictorial examples of several port types will be provided to illustrate the discussion

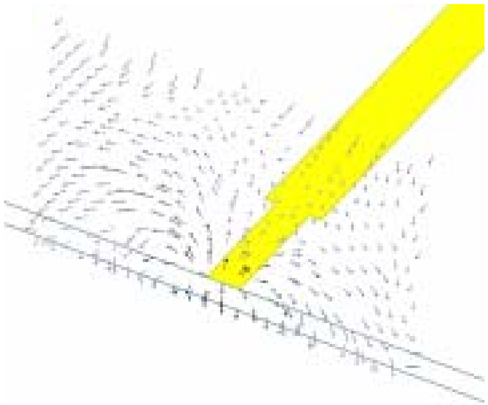


Purpose

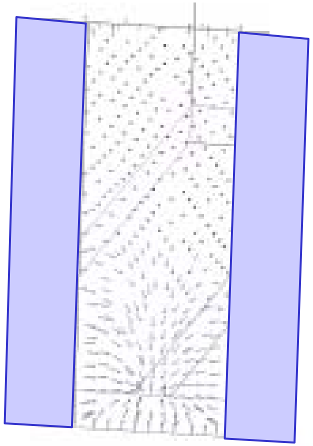
- A Port is a 2D surface on which the fields will be solved according to Maxwell's Equations to determine appropriate RF modal excitations into the 3D model volume. Think of a port as an "aperture" face upon which the field distribution and orientation is known for the steady-state finite element solution
- Wave ports solve actual field distributions in transmission line cross-sections. Lumped ports excite simplified field distributions to permit S-parameter outputs where Wave ports are not feasible.

Characteristics

- Ports should usually exist at locations where they represent cross-sections of a stable transmission line system
  - Note that you can and should draw a smaller 2D 'face' for the port rather than use the entire 'model face' when sizing conditions recommend doing so. This will not constitute a mismatch.
- Port surface area takes on the material characteristics of the materials which touch its face
- Port boundaries take on the boundary characteristics of the boundaries which share its edges
  - Radiation boundaries are the one exception
    - The environment variable ZERO_ORDER_ABC_ON_PORT = 1 can set them to 377 ohms instead
  - Differences exist between Wave and Lumped port bounding assumptions
- Due to the port bounding edges, which may not match boundaries or field behavior in the full 3D volume around the transmission line past the port plane, proper port sizing and location is crucial



A microstrip port at left has sufficient surface area for fringing field behavior, while the one at right forces field attachment to the port side walls, even if the surrounding area was designated as a *radiation* boundary



Characteristics

- Wave ports solve actual field distributions for one or more propagating or non-propagating Modes
  - For “nodal” port excitation references, optional Terminals may also be defined, permitting a single Wave Port to extend across multiple coupled signal conductors. Terminal excitations are built from superposition of Mode excitations.
- Port boundaries take on the boundary characteristics of the faces which share its edges
  - Edges touching perfect_e or finite conductivity faces, such as ground planes, take on that definition
  - Edges touching perfect_h faces become perfect_h edges for the port computation
  - Edges touching symmetry faces take on the definition of the appropriate perfect_e or perfect_h symmetry type
  - Edges touching radiation faces, however, default to perfect_e conductive boundary conditions!
    - The environment variable ZERO_ORDER_ABC_ON_PORT = 1 can set them to 377 ohms instead
- Wave ports solve for characteristic impedance and propagation constants at the port cross-section
- Impedance and Calibration line assignments are optional for further mode and output reference control

Limitations

- Wave ports must have only one surface normal exposed to the 3D field volume
  - Assign to exterior faces (2D objects or faces of solids) of the modeled geometry, or cover one face with a perfect conductor cap object if internal
- Due to the port bounding edges, which may not match boundaries on field behavior in the full 3D volume around the transmission line past the port plane, proper port sizing and location is crucial
- Ports cannot touch master or slave boundaries.
- Due to sizing requirements, Wave ports may not fit between closely spaced yet still isolated transmission lines (e.g. moderately spaced parallel traces)
- Due to the cap object, internalized Wave ports may present undesirable perturbations for antenna or EMI field analysis within the modeled volume
- Wave ports must exist at a sufficient distance from discontinuities in the transmission line structure so that their 2D field solution is appropriate in the context of the 3D, steady-state fields
  - The port extension is the distance between a Wave port and any alteration of the transmission line

Characteristics

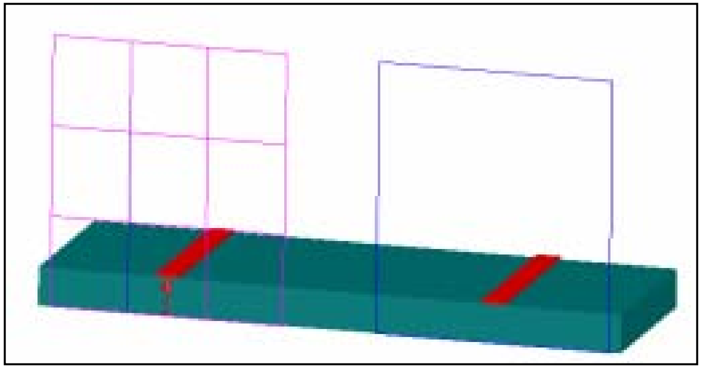
- Lumped ports excite a simplified, single-mode field excitation assuming a user-supplied Zo for S-parameter referencing
  - A Terminal line may still be defined, but only one per port.
  - Impedance and Propagation constants are not computed
- Port boundaries are simplified to support simple uniform field distributions.
  - Edges touching perfect_e or finite conductivity faces, such as ground planes and traces, take on the same definition for the port computation
  - Edges not touching conductors become perfect_h edges for the port computation
    - This is different than the assumption made by Wave ports!!
  - Edges touching symmetry faces take on the definition of the appropriate perfect_e or perfect_h symmetry type
- Impedance and Calibration line assignments are required for Lumped port assignments

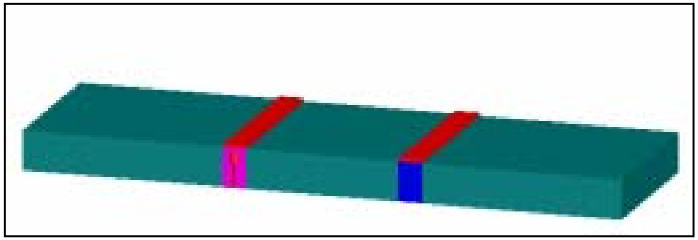
Limitations

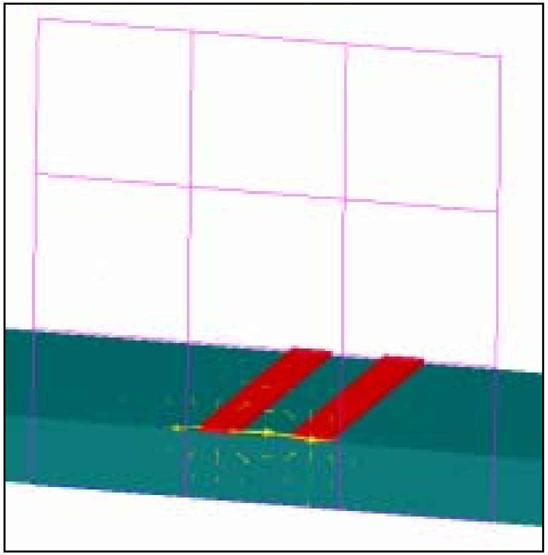
- Lumped ports may be on the outer surface of the model or internal to the model
  - No cap required as with Wave ports
- Ports cannot contact master/slave boundaries
- Lumped ports excite only one mode, and therefore are not appropriate for excitations where modal superposition is expected
  - Lumped ports are not appropriate excitations in closely coupled line structures such as proximal coplanar microstrip traces over a common ground, which should support both even and odd modal behavior
- Since impedance is supplied by the user, not computed, no alternate definitions (Zpi, Zpv, Zvi) are supplied
- Since Propagation constants are not computed, Lumped port S-parameters may not be de-embedded
- Lumped ports should not extend through multiple dielectric volumes
  - Correct usage restricted to lie coplanar to a dielectric face, or extend through only one dielectric material

- Wave Ports are more Rigorous
  - True modal field distribution solution
  - Multiple mode, multiple terminal support
  - Use Wave ports by preference if there are no specific reasons their usage would be discouraged
- Port Spacing may force Selection
  - Widely spaced individual excitations usually permit Wave ports
  - Closer-spaced, yet still individual excitations may require Lumped ports
    - Assumption is that sources are still uncoupled, although there may no longer be room for Wave ports
  - Closely-spaced, coupled excitations require Wave ports
    - Only Wave Ports handle multiple modes, multiple terminals.
- Port Location may force Selection
  - Wave ports are best on model exterior surface; interior use requires cap
  - Lumped ports are best for internal excitations, where caps would provide undue disruption to modeled geometry and fields
  - Wave Ports permit de-embedding to remove excess uniform input transmission lengths
  - Lumped Ports cannot be de-embedded to remove or add uniform input transmission lengths
  - Lumped Ports may be beneficial for ‘internalized’ fields to prevent the need for the port contacting a Master or Slave boundary
- Transmission Line and Solution Frequency may force Selection
  - Lumped Ports support only uniform field distributions
  - Only Wave Ports solve for TE mode distributions, TM mode distributions, or multiple modes in same location
    - Degenerate modes solved for and controlled via per-mode Calibration lines, field polarization
  - Most non-TEM excitations will require Wave Ports

- Spaced by 8 or more times Trace Width
  - Inputs sufficiently isolated that no coupling behavior should occur
  - Sufficient room for Wave port apertures around each trace
  - Use Wave Ports as shown
    - Note ports may be smaller than the entire ‘model face’ by construction of 2D objects solely for port assignment
  - Spaced by 4 – 8 times Trace Width
  - Inputs still fairly isolated, little to no coupling behavior should occur
  - Insufficient room for Wave port apertures around each trace without clipping fringing fields
  - Use Lumped Ports as shown
    - Again, ports are applied to separate 2D geometry objects drawn for the purpose of receiving the port assignment
  - Spaced by less than 4 times Trace Width
  - Traces close enough to exhibit coupling
    - Even and Odd modes possible; N modes total for N conductors and one ground reference [odd mode shown at right]
  - Lumped Ports from trace to ground neglect coupling behavior and are no longer appropriate
  - Use multi-mode Wave Port
    - Terminal line assignments can permit extraction of S-parameters referenced to each ‘trace’

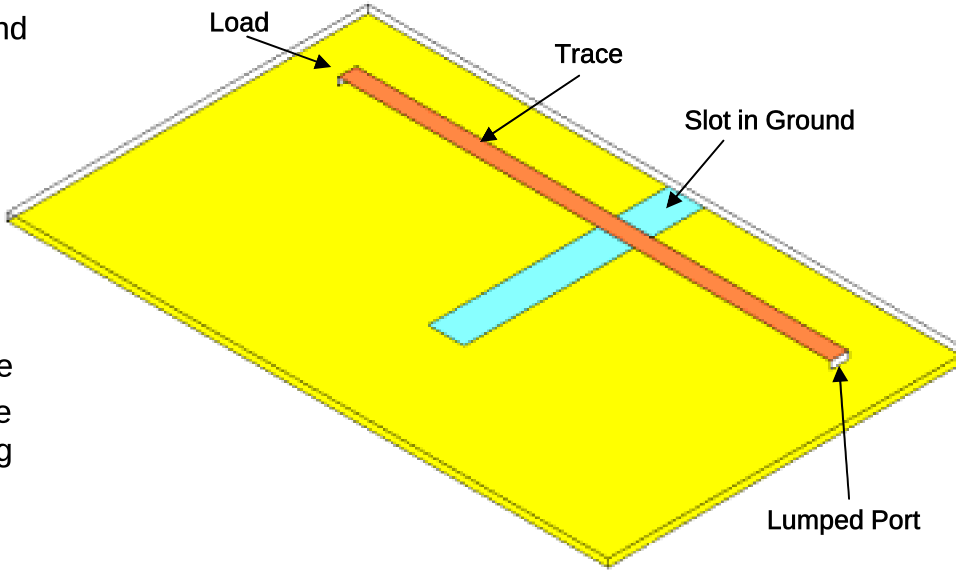




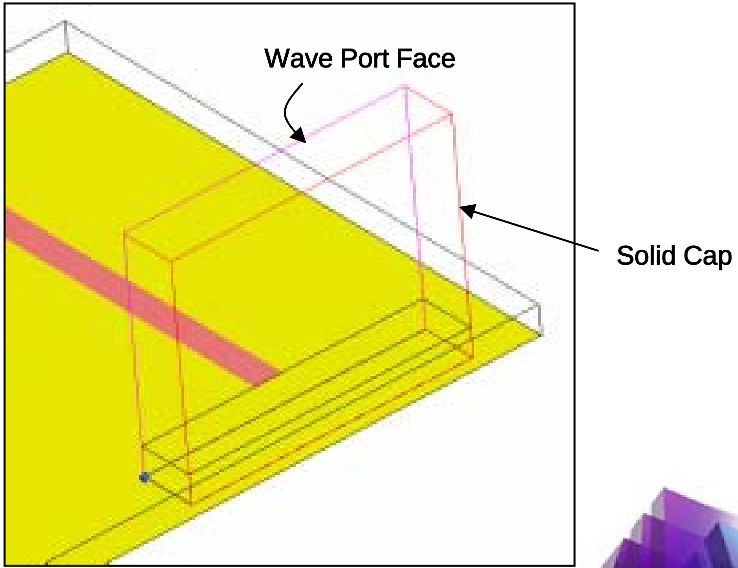


Microstrip Port on RF Board

- Circuit board modeled inside air volume for ground slot excitation and EMI analysis
- Trace does not extend to end of board
  - For above reasons, port must be interior to modeled volume
- Wave port would require cap embedded in substrate [see bottom]
  - Port face extends from ground surface beneath substrate to well above trace plane
  - Cannot have intersecting cap and substrate solids, therefore Boolean subtraction during model construction is required

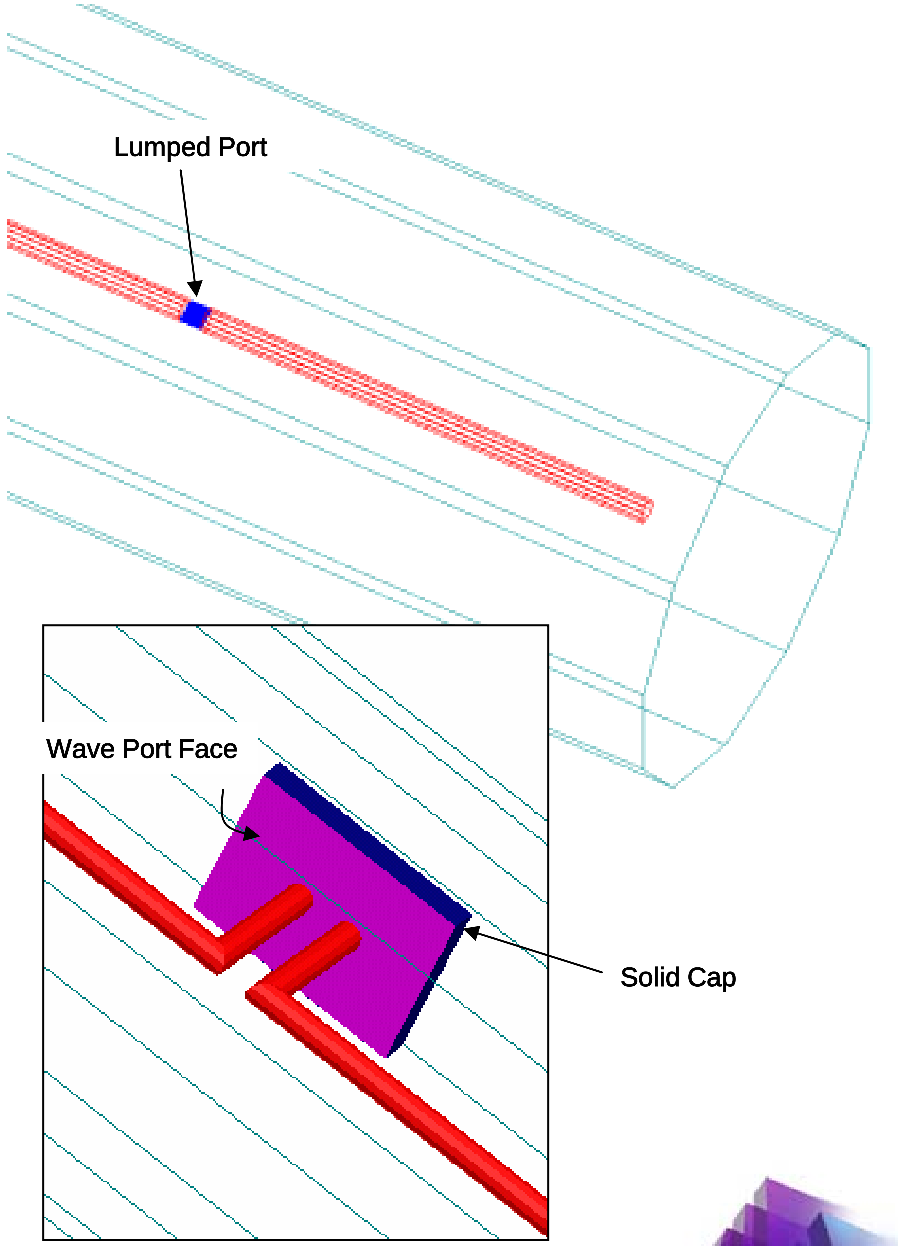


- Use Lumped Port for simplicity
  - Easier to draw
  - Sufficiently accurate solution for isolated line input (no coupled behavior to be neglected)
  - No large metal cap object present to perturb solution of ground plane resonance or radiation effects



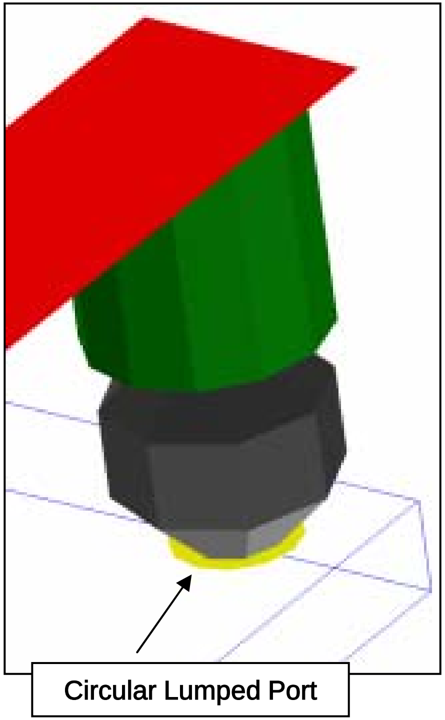
- **Idealized Dipole Antenna**
  - Dipole antenna inside air volume for radiation
  - Wave port internal to volume requires both a uniform transmission line cross section and a cap
  - Large wave port and cap [see below] could influence radiated antenna pattern
  - Difficult to de-embed Wave port solution to junction of dipole antenna to obtain radiation resistance results

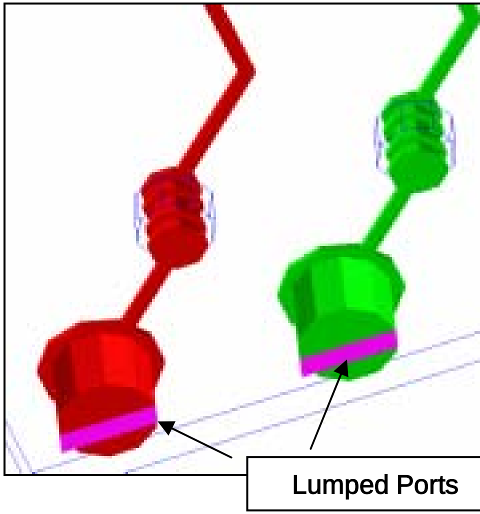
  - Use Lumped Port
    - Lumped port can extend directly between conductors
    - Sufficiently accurate solution for isolated excitation
    - No large cap object to influence radiation pattern results
    - Computation of Z-parameters at port location without any required de-embedding provides radiation resistance



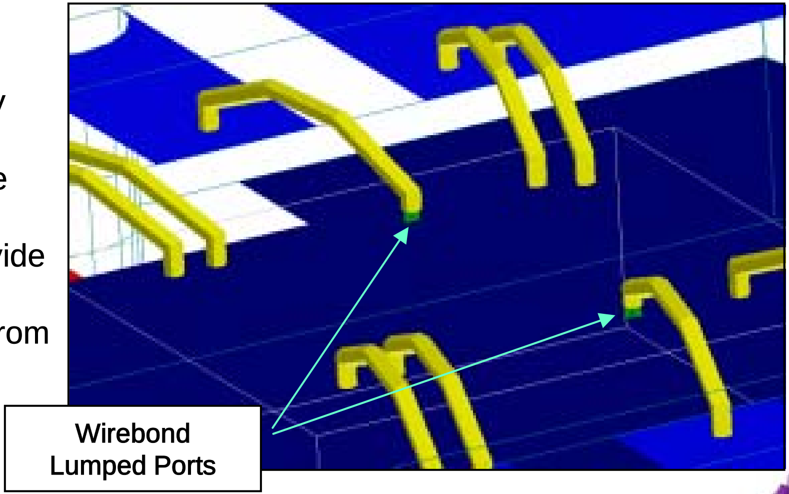
BGA or Wire-Bond Ports

- Ball-Grid Array inputs
  - BGA pitch usually exceeds ball diameter
  - Spacing and field orientation limit coupling between balls
  - Lumped port circles can provide ‘pseudo-coaxial’ excitation beneath spherical balls
    - Impedance and Calibration lines extend from circle diameter to ball diameter
  - Lumped port rectangles between ball and reference ground can provide separate excitations
    - Impedance and Calibration lines extend from ground reference plane to ball (cylinder) bottom
  - Approximations in Lumped port excitations analogous to microprobe measurements





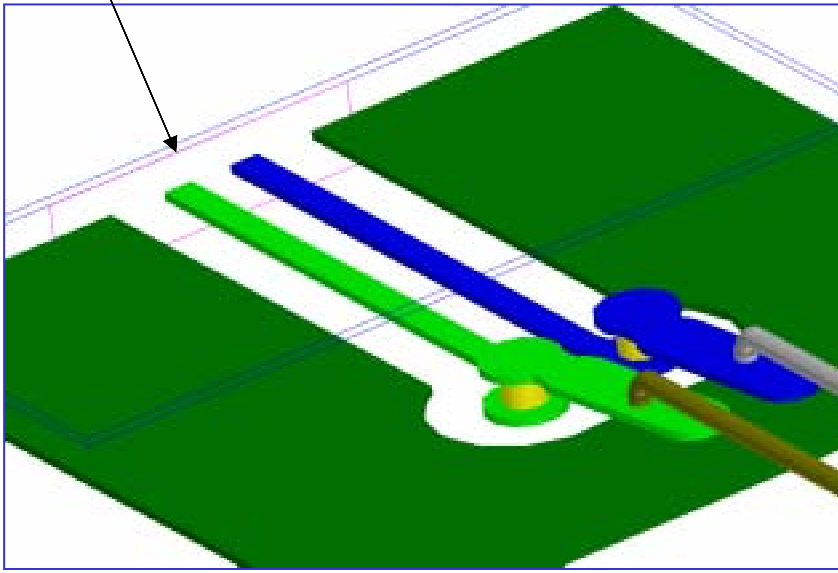
- Wire-bond inputs
  - Wire bond separation usually significantly exceeds wire diameter
  - Coupling between wires may therefore be deemed insignificant
  - Lumped ports from wire to chip solid provide acceptable excitations
    - Cal and Impedance lines vertical from chip to wire

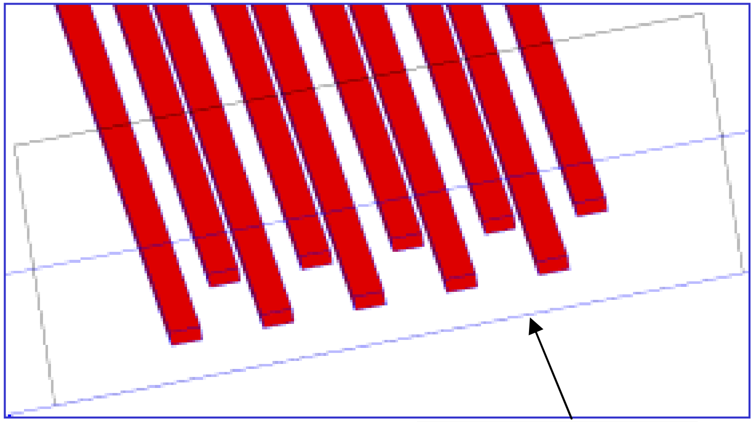


Trace Excitations

- Package or PCB traces that are very tightly spaced and parallel for significant lengths will display strongly coupled behavior
  - Consider proximal traces on adjacent planes without intervening grounds as well
- Likely require Wave Port excitations
  - Solve for N-1 modes for N total conductors
    - One conductor is 'ground reference'. May be port outline.
  - Define Terminal lines for each trace
    - Terminal line references can be a shared ground or other traces, permitting user definition of S-G-S-G type systems [see bottom right]
  - Extract Terminal-based S-matrices in post-processing

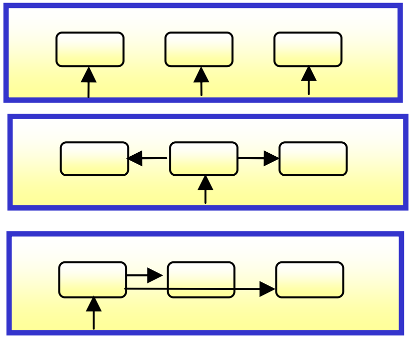
Wave Port Aperture



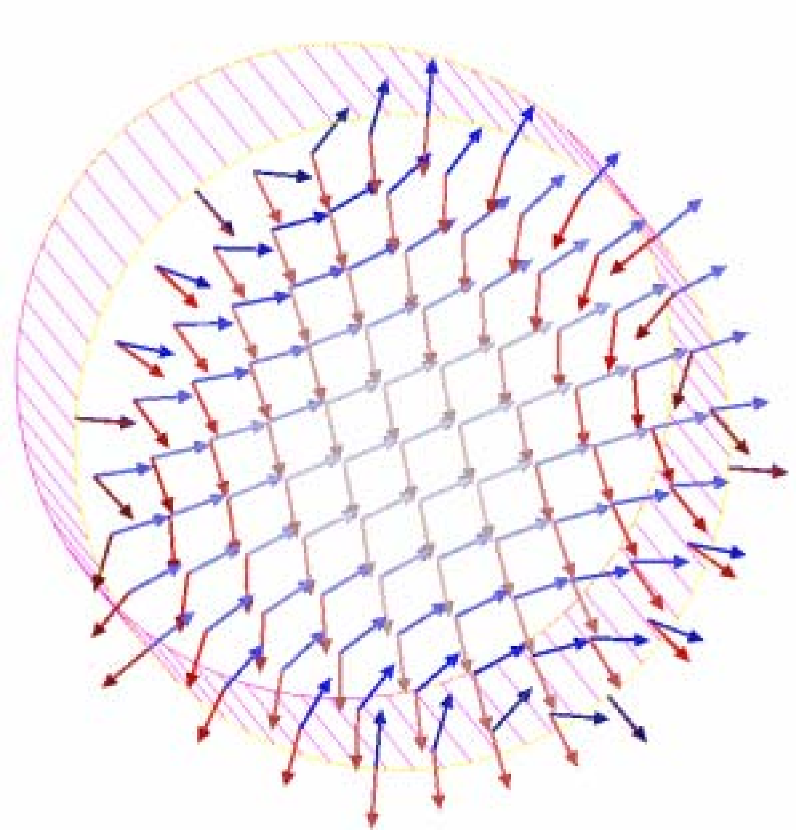


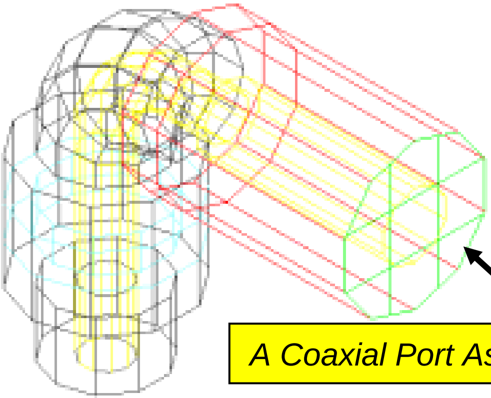
Wave Port Aperture

Possible Terminal Lines for 3 coupled lines over ground plane

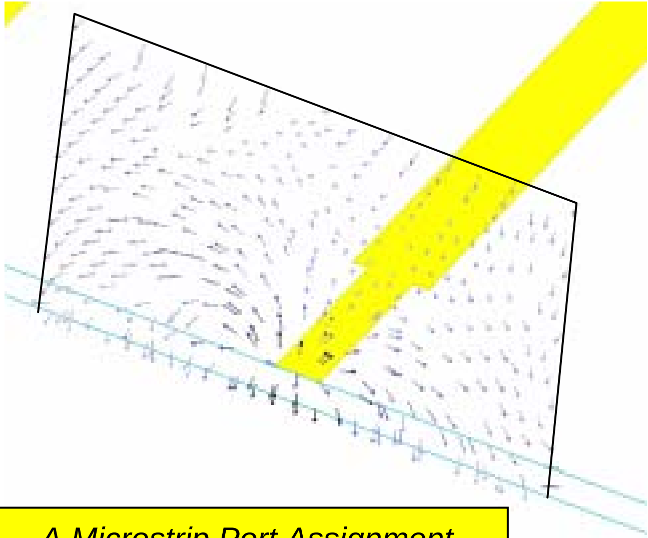


- Waveguide Ports
  - Circular- or Square-symmetric waveguides can carry multiple degenerate TE modes
  - Only Wave Ports permit solving for superposed modal excitations, modal impedances, and modal propagation constants
  - Use Calibration Line if necessary to force E-field polarization for first mode
    - Protects mode ordering, sets phase reference, and prevents mode 'precession' around circular waveguide (WC) ports





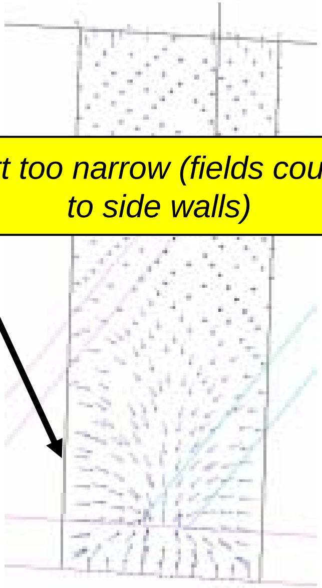
A Coaxial Port Assignment



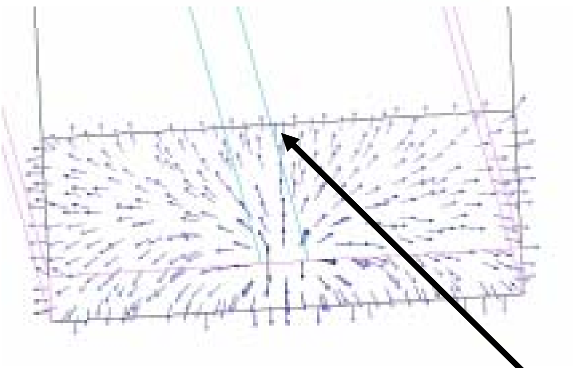
A Microstrip Port Assignment
(includes air above substrate)

- A port is an aperture through which a guided-wave mode of some kind propagates
  - For transmission line structures entirely enclosed in metal, port size is merely the waveguide interior carrying the guided fields
    - Rectangular, Circular, Elliptical, Ridged, Double-Ridged Waveguide
    - Coaxial cable, coaxial waveguide, square-ax, Enclosed microstrip or suspended stripline
  - For unbalanced or non-enclosed lines, however, field propagation in the air around the structure must also be included
- Result: Moving the port edges too close to the circuitry for open waveguide structures (microstrip, stripline, CPW, etc.) will allow coupling from the trace circuitry to the port walls!
  - This causes an incorrect modal solution, which will suffer an immediate discontinuity as the energy is injected past the port into the model volume
    - Parallel Wires or Strips
    - Stripline, Microstrip, Suspended Stripline
    - Slotline, Coplanar Waveguide, etc.

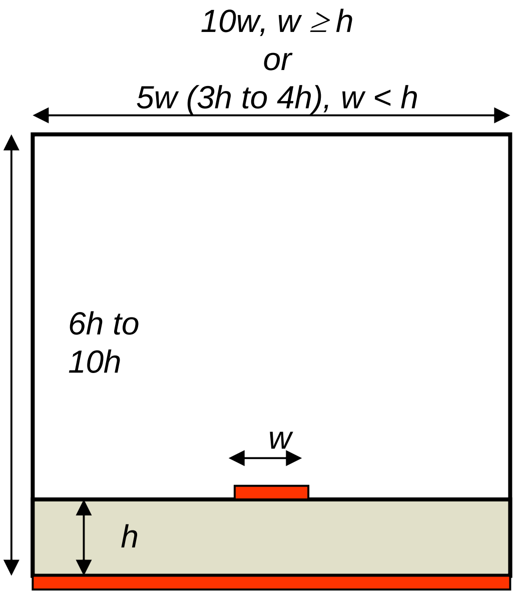
- The port solver only understands conductive boundaries on its borders
  - Electric conductors may be finite or perfect (including Perfect E symmetry)
  - Perfect H symmetry also understood
  - Radiation boundaries around the periphery of the port do not alter the port edge termination!!



Port too narrow (fields couple to side walls)

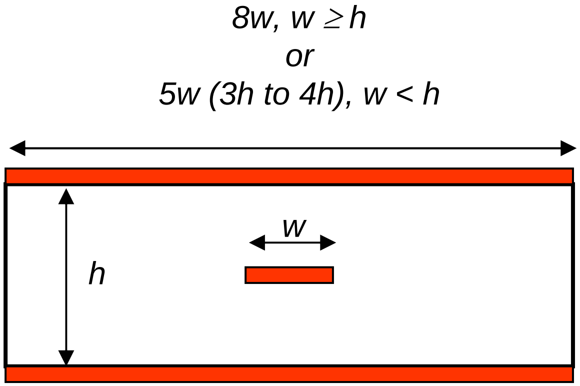


Port too Short (fields couple to top wall)



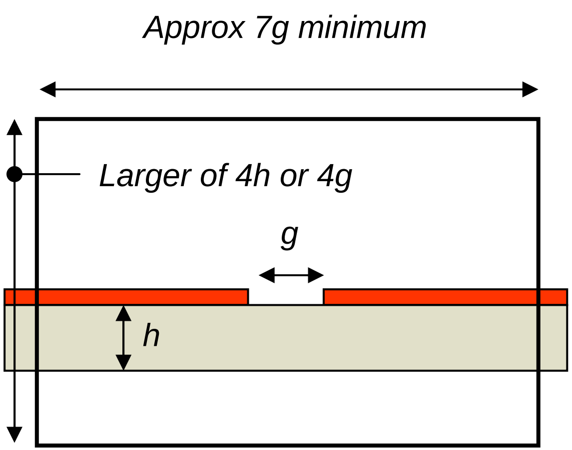
Note: Port sizing guidelines are **not** *inviolable rules true in all cases. For example, if meeting the height and width requirements outlined result in a rectangular aperture bigger than $\lambda/2$ on one dimension, the substrate and trace may be ignored in favor of a waveguide mode. When in doubt, build a simple ports-only model and test.*

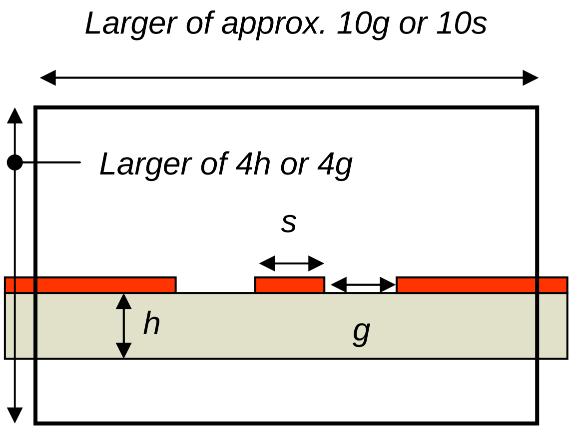
- Microstrip Port Sizing Guidelines
  - Assume width of microstrip trace is *w*
  - Assume height of substrate dielectric is *h*
- Port Height Guidelines
  - Between 6*h* and 10*h*
    - Tend towards upper limit as dielectric constant drops and more fields exist in air rather than substrate
    - Bottom edge of port coplanar with the upper face of ground plane
    - (If real structure is enclosed lower than this guideline, model the real structure!)
- Port Width Guidelines
  - 10*w*, for microstrip profiles with $w \geq h$
  - 5*w*, or on the order of 3*h* to 4*h*, for microstrip profiles with $w < h$



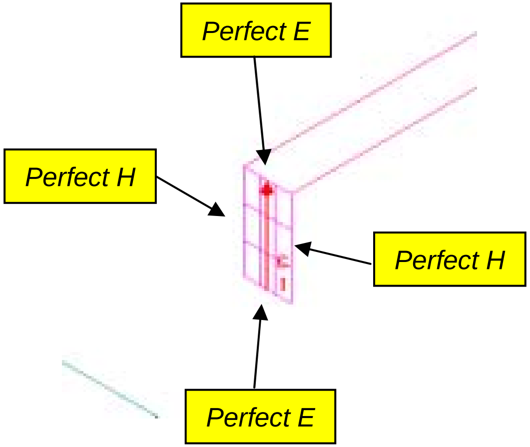
- Stripline Port Sizing Guidelines
  - Assume width of stripline trace is *w*
  - Assume height of substrate dielectric is *h*
- Port Height Guidelines
  - Extend from upper to lower groundplane, *h*
- Port Width Guidelines
  - 8*w,* for microstrip profiles with $w \geq h$
  - 5*w,* or on the order of 3*h* to 4*h*, for microstrip profiles with $w < h$
- Boundary Note: Can also make side walls of port *Perfect H* boundaries

- Slotline Port Guidelines
  - Assume slot width is *g*
  - Assume dielectric height is *h*
- Port Height:
  - Should be at least 4*h,* or 4*g* (larger)
  - Remember to include air below the substrate as well as above!
    - If ground plane is present, port should terminate at ground plane
- Port Width:
  - Should contain at least 3*g* to either side of slot, or 7*g* total minimum
  - Port boundary *must* intersect both side ground planes, or they will 'float' and become signal conductors relative to outline 'ground'

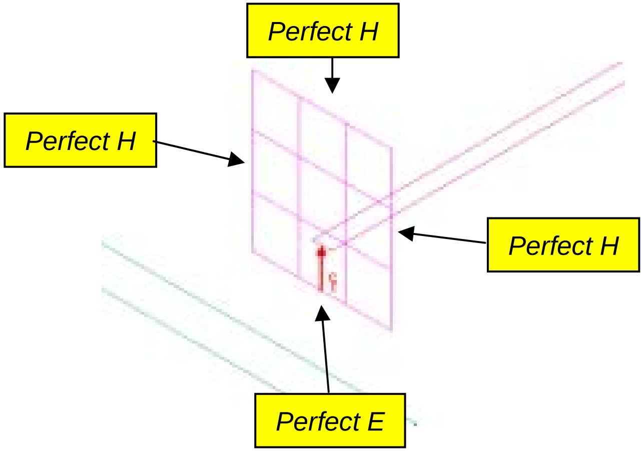




- CPW Port Guidelines
  - Assume slot width is *g*
  - Assume dielectric height is *h*
  - Assume center strip width is *s*
- Port Height:
  - Should be at least 4*h,* or 4*g* (larger)
  - Remember to include air below the substrate as well as above!
    - If ground plane is present, port should terminate at ground plane
- Port Width:
  - Should contain 3-5*g* *or* 3-5*s* of the side grounds, whichever is larger
    - Total about 10*g* *or* 10*s*
  - Port outline *must* intersect side grounds, or they will ‘float’ and become additional signal conductors along with the center strip.



- *Gap Source* ports behave differently from Standard Ports
  - Any port edge not in contact with metal structure *or* another port assumed to be a Perfect H conductor
- Gap Source Port Sizing (microstrip example):
  - *"Strip-like": [RECOMMENDED]* No larger than necessary to connect the trace width to the ground
  - *"Wave-like":* No larger than 4 times the strip width and 3 times the substrate height
    - The *Perfect H* walls allow size to be smaller than a standard port would be
    - However, in most cases the *strip-like* application should be as or more accurate



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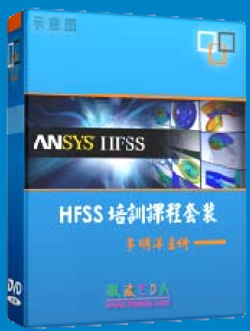

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