Common Mode Filters

X2Y® Capacitors
vs.
Common Mode Filters
Contents

• Common and Differential Mode Noise
• Mode Conversion
• Filter Solutions
• Test Comparisons
• Comparative Applications
• X2Y Capacitor Selection Methodology
• Mounting Suggestions
Common Mode and EMI

- Most EMI compliance problems are common mode emissions.
- Only 10’s of uAs in external cables are enough to violate EMC standards.
Common Mode Radiated Noise Model

- E field developed between any lead exiting a shielded enclosure and the enclosure outer skin radiates.
- Complementary H field couples to victim antennae.
- Ability to radiate depends on:
  - Power in the noise source
  - Coupling efficiency between the effective antenna structure and the surrounding space
    - Leads and case form the antenna
Common Mode Radiated Noise Model

- Device w/o metallic case: “CM” develops between dominant external metal, such as Vss solid polygon, or hatch.
Common Mode Radiated Noise Model

- Reduce radiation by:
  - Reducing potential between the case and leads, AND/OR
  - Reducing coupling efficiency to surrounding space
    - Reduce antenna gain.
    - Mismatch source impedance to the antenna impedance.
Reduce CM Source Power

• Reduce HF current in product
  – Rarely an option
• Decrease shunt impedance to case
  – Optionally insert additional series impedance between source and shunt
  – Effectiveness requires low impedance compared to the source and antenna.
Reduce Coupling

- Reduce antenna efficiency
  - Cable length
  - Cable routing / shielding
- Mismatch antenna impedance
  - Increase driving impedance $>> 377 \text{ Ohms}*$
    - Inserted $Z$ effective when $>> \frac{Z_{\text{SOURCE}} + Z_{\text{ANTENNA}}}{Z_{\text{ANTENNA}}}$
  - Decrease driving impedance $<< 377 \text{ Ohms}*$
    - Inserted $Z$ effective when $<< Z_{\text{ANTENNA}}$

*Antenna impedance may be anywhere from 10’s to 100’s of Ohms
Typically 100 – 180 Ohms
EMI Filter Attenuation

NO FILTER

\[ P_{\text{ANTENNA}} = \frac{V_{\text{ANTENNA}}^2}{Z_{\text{ANTENNA}}} \]
\[ V_{\text{ANTENNA}} = \frac{V_S \cdot Z_A}{Z_S + Z_A} \]

SERIES FILTER (High Z)

\[ V_{\text{ANTENNA}} = \frac{V_S \cdot Z_A}{Z_S + Z_A + Z_{\text{CM}}} \]
\[ V_{\text{ANTENNA}} / V_{\text{ANTENNA\_NOFILTER}} = \frac{Z_S + Z_A}{Z_S + Z_A + Z_{\text{CM}}} \]

EFFECTIVENESS CRITERIA:
\[ Z_{\text{CM}} \gg (Z_S + Z_A) \]

SHUNT FILTER (Low Z)

\[ V_{\text{ANTENNA}} = \frac{V_S \cdot (Z_S || Z_X)}{Z_S || Z_A} \]
\[ V_{\text{ANTENNA}} / V_{\text{ANTENNA\_NOFILTER}} = Z_X / (Z_X + (Z_S || Z_A)) \]

EFFECTIVENESS CRITERIA:
\[ Z_X \ll Z_S || Z_A \]
Differential Mode Radiated Noise Model

- Voltage(s) between multiple leads that form an antenna in the area between.
Mode Conversion

• Occurs when individual filters are not matched.
• Differential signal energy converts into common-mode energy.
• Common-mode energy converts into differential energy.
• Avoid by matching filters throughout stop-band.
• Not an emissions concern where signals do not exist in the noise stop band.
• Mode conversion is a susceptibility concern at all frequencies.
Single Chokes / Beads as EMI Filters

- Chokes attenuate noise emissions when they substantially increase the total noise source impedance relative to the antenna impedance.
  - Insertion loss in dB is:
    - \(20 \log\left(\frac{Z_S + Z_A}{Z_S + Z_A + Z_{\text{CHOKE}}}\right)\)

- Bead impedance is limited by effective parallel resistance.
  - 600 Ohm bead max insertion loss:
    - -17dB: 50Ω source / 50Ω antenna
    - -12dB: 50Ω source / 150Ω antenna

- Chokes and beads limited at high frequency by parasitic mounted capacitance.
  - Device & mounting structure capacitance in parallel
  - PCB layout & adjacent components can defeat insertion loss
CM Choke Mechanics

- A CM choke couples chokes on a common core
  - Usually two windings / core.
  - Coupling improves CM rejection on each lead in the stop band,
  - CM chokes can pass differential signals in the stop band.

- A CM choke is a 1:1 transformer where the primary and secondary are both driven.
  - Both windings act as both primary and secondary.
  - Current through one winding induces an opposing current in the other winding.
  - For K close to 1.0, total effective CM impedance is:
    - $Z \approx 2\pi F L_{\text{mag}}$
    - 2X what two independent chokes with the same $L_{\text{mag}}$ would yield.

\[ I_{\text{OUT}} = 2(V_{\text{IN}}/Z(1+K)) \]

CM CHOKES, 0.98 <= K <= 0.99
CM Choke Mechanics

- CM choke winding coupling **DOES NOT** cancel all or even a high percentage of CM noise.
- CM chokes **DO** increase CM inductance up to **2X** compared to each of two independent chokes of the same open circuit inductance rating.
- CM chokes **DO** cancel most core flux allowing much higher CM currents w/o saturation than two independent chokes of the same material and core size.
  - Allows DC and AC to pass as differential currents w/o killing CM attenuating inductance
  - Important to power filter applications that use chokes
    - DC balance must be maintained in wiring and load.
CM Choke Mechanics

• Just as with individual chokes / beads, parasitic capacitance limits the effective frequency range of CM chokes.

• For a given core material, the higher the inductance used to obtain lower frequency filtering, the greater the number of turns required and consequent parasitic capacitance that defeats high frequency filtering.

• At frequencies > $F_{SRF}$, parasitic capacitance defeats impedance gain from coupled windings.

Capacitor current bypasses the transformer coupling. At frequencies > $F_{RES}$, impedance is capacitive and low.
Choke/Bead/CM Choke Bandstop

• Insertion loss declines past $F_{SRF}$ due to parasitic shunt capacitance.
  – Parasitic capacitance, noise source impedance and lead antenna impedance define high frequency noise attenuation.
  – Parasitic capacitance is combined effects of the CM Choke and the CM Choke PCB mount.
  – Very small capacitances, < 1pF can have very big effects above 100MHz
  – 1pF Limits 1GHz Insertion Loss:
    • -8dB: 50Ω source / 50Ω antenna
    • -5dB: 50Ω source / 150Ω antenna
  – $F_{SRF} = 1/(2\pi(\sqrt{L_{CM} \cdot C_{PAR}}))$
CM Chokes Winding Mismatch

- Mismatch between windings from mechanical manufacturing tolerance causes mode conversion.
  - A percentage of signal energy converts to common mode, and vice-versa.
  - This gives rise to EMC issues as well as immunity issues.
- Mismatch reduces the effective inductance in each leg.
  - $L_{\text{EFF}} \approx L_{\text{MAG}} \times (1 + K_{\text{MATCH}})$
  - $0.9 < K_{\text{MATCH}} < 0.99$
CMCs Stop Band Mode Conversion

- Parasitic capacitance and winding mismatch both defeat inductive cancellation in the stop band causing mode conversion.
- Not a major radiation concern where signal energy is negligible in the stop band.
  - Conditions under which a shunt filter is a viable alternative.
CMCs Mode Conversion Susceptibility

- ESD discharge onto case induces common mode voltage onto cables.
  - Standard test waveform leading edge knee frequency: 300-500MHz

- Mode conversion increases susceptibility of internal circuits to outside noise:
  - 1% Magnetics mismatch => 2% of CM voltage appears as difference voltage across leads

- Similar mechanics for power leads.
CMCs Mode Conversion Susceptibility

• At frequencies above filter $F_{SRF}$, voltage passed through each winding depends on:
  – Choke parasitic capacitance,
  – Layout, and
  – IC input matching.

• Add transient voltage suppression devices, TVS, to protect ICs / power system.
CM Chokes as EMI Filters

• CM chokes have one really good application:
  – Signals must be passed that operate in the same frequency range as CM noise that must be suppressed.
  – Mode conversion and winding mismatch is a major concern in these applications.

• Otherwise: CM chokes are: large, heavy, expensive, and subject to vibration induced failure.

• Estimating CM performance
  – Example: 4.7mH $L_{CM}$, 3pF $C_{PAR}$:
    – $F_{SRF} = 1.3$MHz
    – $IL_{dBMAX} = 20\log(100/8.4E6)$
    – $\approx -52$dB
X2Y® Capacitors, Nearly Ideal Shunts

• Two closely matched capacitors in one package.
  • Effects of temperature and voltage variation eliminated
  • Effect of ageing equal on both lines

• Very low inductance between terminals.
X2Y® Capacitors, Nearly Ideal Shunts

• When properly applied, X2Y® capacitors filter CM noise by *both* attenuating source energy, and mismatching antenna impedance.
• The key is very low, and matched inductance.
• Proper application must mind inductance in the common path: G1/G2 terminals.

![X2Y® Circuit 1 CM Filter](image)

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X2Y® Capacitors, Nearly Ideal Shunts

- X2Y® capacitor shunts between A, B, and G1/G2 attachments.
  - Component inductance is very low:
    - ≈110pH from each A or B to G1/G2.

- Low impedance shunt serves two purposes:
  - Divides noise voltage
  - Mismatches external antenna impedance
    - Reflects inside noise back inside
    - Reflects external noise: EFT/ESD back towards outside.

- Performance is typically limited by external capacitor mounting inductance relative to protected traces and RF common:
  - L3A/L3B, L4A, L4B
  - Minimize with best practices
    - See slides 52-54 for technique
  - RF common is the case for metallic enclosures.
  - RF common is circuit common for non-metallic enclosures

X2Y® Circuit 1 CM Filter

RF COMMON

RF COMMON

V+

V−

PCB TRACE INDUCTANCE

X2Y® SIMPLIFIED EQUIVALENT CIRCUIT

CAPACITOR MOUNTING INDUCTANCE

L1A

L2A

L3A

L4A

G1

L3B

L4B

G2

L1B

L2B

X2Y® CAPACITOR ATTENUATORS, LLC
Confidential Information

5/21/2011
X2Y® Bandstop

• Insertion loss builds up to $F_{SRF}$ due to parallel capacitance.

• Insertion loss declines past $F_{SRF}$ due to parasitic common inductance.

• Y capacitor mismatch reduces insertion loss below $F_{SRF}$.
  – Increases low frequency cut-off by $\approx 2/(1 + K_{\text{MATCH}})$
  – $0.9 < K_{\text{MATCH}} < 0.99$
  – Generally no concern
X2Y® vs. CM Choke Bandstop

Insertion Loss Characteristics

-1 Slope Shunt Capacitance

+1 Slope Common Inductance

Z_{SOURCE} = 50 \text{ Ohms}
C_Y = 4.7 \text{ nF}
K_{MATCH} = 95\%
ESL 1 side = 280 \text{ pH}
Z_{TX-CM} = 50 \text{ Ohms}

-10dB 3.7MHz - 5.3GHz
-20dB 14MHz - 1.4GHz

≈ 18dB
150MHz - 1GHz
X2Y® Bandstop

• **Insertion Loss:**
  \[ 20 \log\left(\frac{Z_{X2Y}}{Z_{X2Y}+(Z_{SOURCE} || Z_{ANTENNA})}\right) \]

• **Low frequency performance** determined by X2Y® capacitance.
  - Increase capacitance as required to set filter lower cut-off frequency.

• **High frequency attenuation** determined by:
  - Mounted capacitor common inductance.
  - Essentially constant across X2Y® values.

• **Insertion Loss @1GHz**
  - Using 4mil top dielectric PCB
  - -24dB: 50Ω \(Z_{SOURCE} / 50Ω \ Z_{ANTENNA}\)
  - -27dB: 50Ω \(Z_{SOURCE} / 150Ω \ Z_{ANTENNA}\)

• **Unique X2Y® advantage:**
  - Larger capacitors do not hurt HF performance.
**X2Y® and ESD/EFT Susceptibility**

- **X2Y®** is a shunt solution with very low and **matched** parasitic inductance.
  - Common mode attenuation is high over a wide frequency range.
  - Mode conversion has two contributors:
    - @Low frequencies: capacitor value matching.
    - @High frequencies: inductance matching.
- Mode conversion for 1nF and larger parts, @ 350MHz is better than -50dB
X2Y® and ESD/EFT Susceptibility

Measured Common to Differential Mode Conversion
X2Y® 0603 Capacitors

-10dB
-20dB
-30dB
-40dB
-50dB
-60dB
-70dB

100kHz 1MHz 10MHz 100MHz 1GHz 10GHz

Low Frequency Mode Conversion Peaks Limited by Capacitance Match
High Frequency Mode Conversion Peaks Limited by Mounted Inductance / TxLine Z Match

10nF
1nF
100nF
1μF

350MHz F_KNEE
IEC 61000-2-4
ESD Waveform
Test Comparisons

• Test Setup
  – Agilent 85033D 3.5mm Calibration Kit
  – Agilent E5071C ENA Network Analyzer
    • 100 kHz - 8.5 GHz
    • Balanced measurements (4-port option)
  – DUT test board
Test PCBs

Calibration Positions on PCB

Short/Open/Load/Through (SOLT) calibration is used to de-embed the test fixture effects.

Inductor DUTs

X2Y® Capacitor DUTs
Mixed-Mode Derivations

• Mixed-mode measurements are derived mathematically from full four-port single-ended VNA measurements.
• The Agilent E5071C VNA includes the matrix manipulation software to perform these transformations.
• Of key importance are:
  – SCC21/SCC12 common mode rejection from one side to the other
    • Measures EMI filter effectiveness
  – SDC21/SDC12 common mode to differentiation conversion from one side to the other
    • Measures ESD suppression effectiveness
Mixed-Mode Derivations

SINGLE-ENDED MEASUREMENTS

\[
\begin{bmatrix}
S_{11} & S_{12} & S_{13} & S_{14} \\
S_{21} & S_{22} & S_{23} & S_{24} \\
S_{31} & S_{32} & S_{33} & S_{34} \\
S_{41} & S_{42} & S_{43} & S_{44}
\end{bmatrix}
\]

DEST PORT \quad SOURCE PORT

ARITHMETICALLY DERIVED VIRTUAL MIXED MODE PORT 1

SIGA

\[\begin{align*}
50 \Omega & \\
\frac{V_{DM}}{2} & \\
\frac{V_{CM}}{2} & \\
50 \Omega &
\end{align*}\]

ARITHMETICALLY DERIVED VIRTUAL MIXED MODE PORT 2

SIGA

\[\begin{align*}
50 \Omega & \\
\frac{V_{DM}}{2} & \\
\frac{V_{CM}}{2} & \\
50 \Omega &
\end{align*}\]

DUT

\[\begin{align*}
100 \Omega & \\
V_{DM1} & \\
25 \Omega & \\
V_{CM1} &
\end{align*}\]

\[\begin{align*}
100 \Omega & \\
V_{DM2} & \\
25 \Omega & \\
V_{CM2} &
\end{align*}\]

MIXED-MODE SPARMETERS

\[
\begin{bmatrix}
S_{DD11} & S_{DD12} & S_{DC11} & S_{DC12} \\
S_{DD21} & S_{DD22} & S_{DC21} & S_{DC22} \\
S_{CD11} & S_{CD12} & S_{CC11} & S_{CC12} \\
S_{CD21} & S_{CD22} & S_{CC21} & S_{CC22}
\end{bmatrix}
\]
Common Mode Derivation

- **Goal:** Determine the amount of common mode energy relative to ground driving Ports 1 and 3 that reaches Ports 2 and 4.
  - Indicates EMI suppression performance
- **Both Port 1 and Port 3 drive CM energy in parallel.**
  - The two parallel 50Ω ports appear as 25Ω on each side of the filter.
- **Operation is symmetric:**
  - $S_{CC21}$ matches $S_{CC12}$
Common Mode Derivation

SINGLE-ENDED MEASUREMENTS

\[
\begin{bmatrix}
S_{11} & S_{12} & S_{13} & S_{14} \\
S_{21} & S_{22} & S_{23} & S_{24} \\
S_{31} & S_{32} & S_{33} & S_{34} \\
S_{41} & S_{42} & S_{43} & S_{44}
\end{bmatrix}
\]

DEST PORT

SOURCE PORT

ARITHMETICALLY DERIVED VIRTUAL MIXED MODE PORT 1

ARITHMETICALLY DERIVED VIRTUAL MIXED MODE PORT 2

MIXED-MODE SPARPARAMETERS

\[
\begin{bmatrix}
S_{DD11} & S_{DD12} & S_{DC11} & S_{DC12} \\
S_{DD21} & S_{DD22} & S_{DC21} & S_{DC22} \\
S_{CD11} & S_{CD12} & S_{CC11} & S_{CC12} \\
S_{CD21} & S_{CD22} & S_{CC21} & S_{CC22}
\end{bmatrix}
\]

SCC21: Common Mode from P1 to P2

For linear networks: \( S_{CC12} = S_{CC21} \)
Common to Diff Mode Conversion Derivation

- **Goal:** Determine the amount of common mode noise from the external port that converts to differential energy across the internal ports.
  - Indicates immunity to interference: cell phone, ESD, EFT, etc.
- CM input is two parallel 50Ω sources, 25Ω net.
- DM output appears across series 50Ω loads, 100Ω net.
- Operation is symmetric:
  - \( S_{DC21} \) matches \( S_{DC12} \)
Common to Diff Mode Conversion Derivation

SINGLE-ENDED MEASUREMENTS

```
<table>
<thead>
<tr>
<th>S11</th>
<th>S12</th>
<th>S13</th>
<th>S14</th>
</tr>
</thead>
<tbody>
<tr>
<td>S21</td>
<td>S22</td>
<td>S23</td>
<td>S24</td>
</tr>
<tr>
<td>S31</td>
<td>S32</td>
<td>S33</td>
<td>S34</td>
</tr>
<tr>
<td>S41</td>
<td>S42</td>
<td>S43</td>
<td>S44</td>
</tr>
</tbody>
</table>
```

DEST PORT

SOURCE PORT

ARITHMETICALLY DERIVED VIRTUAL MIXED MODE PORT 1

50 Ω

SIGA

100 Ω

VDM1

VCM1

25 Ω

SIGB

50 Ω

ARITHMETICALLY DERIVED VIRTUAL MIXED MODE PORT 2

100 Ω

VDM2

VDM

Mixed-Mode SPARARAMETERS

```
<table>
<thead>
<tr>
<th>SDD11</th>
<th>SDD12</th>
<th>SDC11</th>
<th>SDC12</th>
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<tbody>
<tr>
<td>SDD21</td>
<td>SDD22</td>
<td>SDC21</td>
<td>SDC22</td>
</tr>
<tr>
<td>SCD11</td>
<td>SCD12</td>
<td>SCC11</td>
<td>SCC12</td>
</tr>
<tr>
<td>SCD21</td>
<td>SCD22</td>
<td>SCC21</td>
<td>SCC22</td>
</tr>
</tbody>
</table>
```

S_{DC21}: Mode Conversion
Common Mode from P1 to Differential Mode P2

For linear networks: \( S_{DC12} = S_{DC21} \)
## DUTs

<table>
<thead>
<tr>
<th>DUT</th>
<th>Component Size (mm)</th>
<th>DC Current Rating</th>
<th>Pic</th>
</tr>
</thead>
<tbody>
<tr>
<td>X2Y® 1812</td>
<td>4.4 x 3.2</td>
<td>In bypass, no current limit</td>
<td><img src="X2YAttenuators.png" alt="Image" /></td>
</tr>
<tr>
<td>X2Y® 1206</td>
<td>3.2 x 1.6</td>
<td>In bypass, no current limit</td>
<td><img src="X2YAttenuators.png" alt="Image" /></td>
</tr>
<tr>
<td>X2Y® 0603</td>
<td>1.6 x 0.8</td>
<td>In bypass, no current limit</td>
<td><img src="X2YAttenuators.png" alt="Image" /></td>
</tr>
<tr>
<td>(1) 4000 Ohm Common Mode Choke</td>
<td>5.0 x 3.6</td>
<td>200 mAmps</td>
<td><img src="X2YAttenuators.png" alt="Image" /></td>
</tr>
<tr>
<td>(1) 1000 Ohm Common Mode Choke</td>
<td>5.0 x 4.7</td>
<td>1500 mAmps</td>
<td><img src="X2YAttenuators.png" alt="Image" /></td>
</tr>
<tr>
<td>(1) 4.7 mH Common Mode Choke A</td>
<td>9.0 x 6.0</td>
<td>400 mAmps</td>
<td><img src="X2YAttenuators.png" alt="Image" /></td>
</tr>
<tr>
<td>(1) 4.7mH Common Mode Choke B</td>
<td>9.3 x 5.9</td>
<td>400 mAmps</td>
<td><img src="X2YAttenuators.png" alt="Image" /></td>
</tr>
<tr>
<td>(2) 1uH Chip Inductors</td>
<td>(2) 3.2 x 1.6</td>
<td>1200 mAmps</td>
<td><img src="X2YAttenuators.png" alt="Image" /></td>
</tr>
<tr>
<td>(2) 120 Ohm Ferrite beads</td>
<td>(2) 3.2 x 1.6</td>
<td>3000 mAmps</td>
<td><img src="X2YAttenuators.png" alt="Image" /></td>
</tr>
<tr>
<td>(2) 600 Ohm Ferrite beads</td>
<td>(2) 3.2 x 1.6</td>
<td>3000 mAmps</td>
<td><img src="X2YAttenuators.png" alt="Image" /></td>
</tr>
</tbody>
</table>
Footprint Comparisons

X2Y® CAPACITORS SUPERIMPOSED OVER MAGNETIC CM FILTERS
Common Mode Rejection Performance

- CM Rejection at frequencies > 100MHz is generally weak with magnetics
  - Interwinding capacitance bypasses series inductance at high frequencies.
  - Ferrite interdomain capacitance bypasses series loss at high frequencies.
Common Mode Rejection Performance

- Rejection ratio degrades for real antenna $Z > 50\Omega$
  - $120 - 180$ Ohms typical
  - $150\Omega$ degrades by
    - $6$ dB at high loss,
    - $\approx 3$ dB near $10$ dB
- Where $Z_{CM} \gg (Z_S + Z_A)$:
  - Loss $\approx 20\log(Z_S + Z_A)/(Z_{CM})$
  - Increasing $Z_A$ from $50$ to $150$ doubles $(Z_S + Z_A)$
Common Mode Rejection Performance

- Low frequency chokes:
  - Capable of good insertion loss at modest frequencies.
  - Capacitive parasitics reduce attenuation to 20dB or less @ 100MHz
- Resonances create unstable insertion loss @ high frequencies.
  - Actual insertion loss highly dependent on:
    - Circuit source impedance
    - Cable geometry

![Graph showing measured common mode rejection performance with popular CM chokes/beads for 50 Ohm Zsource, 50 Ohm Zantenna]
Common Mode Rejection Performance

- Complex HF resonances
  - High inductance / capacitance chokes exhibit complex interactions with PCB traces, connectors, & cables @ high frequencies.
  - As frequency moves between odd and even 1/4\(\lambda\) multiples of cable lengths, unterminated cable noise attenuation moves between local minima and maxima.
Common Mode Rejection Performance

- High frequency chokes / beads
  - Bead insertion loss limited by parasitic resistance and capacitance.
  - 600 Ohm bead limits max. insertion loss to -17dB
  - 1pF limits insertion loss @ 1GHz to -8dB
    - Must include PCB parasitics
    - Nearby etch or parts can destroy HF insertion loss
Common Mode Rejection X2Y®

- Consistent high frequency performance independent of capacitance.
  - Mounted inductance controls
  - Linear decrease in noise attenuation w/frequency
  - 0603 parts -24dB or better @ 1GHz into 25 Ohm even mode impedance.

- Capacitor value only affects low frequency attenuation.
  - Larger capacitance values filter lower frequencies

Insertion Loss dB = 20LOG(Z_{X2Y}/(Z_{X2Y} + (Z_{SOURCE} || Z_{ANTENNA})))
Common Mode Rejection X2Y®

- Rejection ratio improves for real antenna $Z > 50\,\Omega$
  - $120\,\Omega$ – $180\,\Omega$ Ohms typical
  - $150\,\Omega$ improves by
    - 2.5dB at high loss, (>20dB)
- Where $Z_{X2Y} < (|Z_S| |Z_A|)$:
  - Loss $\approx 20\text{LOG}(Z_{X2Y})/(|Z_S| |Z_A|)$
  - Increasing $Z_A$ from 50Ω VNA port to 150Ω practical antenna value decreases $(|Z_S| |Z_A|)$ by 0.75:1.
Common Mode Rejection Comparisons

Measured Common Mode Rejection
Popular CM Chokes / Beads
50 Ohm $Z_{\text{SOURCE}}$, 50 Ohm $Z_{\text{ANTENNA}}$

Insertion Loss dB = $20 \log \left( \frac{Z_{\text{SOURCE}} + Z_{\text{ANTENNA}}}{Z_{\text{SOURCE}} + Z_{\text{ANTENNA}} + Z_{\text{CM}}} \right)$
Common Mode Rejection Comparisons

Measured Common Mode Rejection
Popular CM Chokes / Beads
50 Ohm $Z_{\text{SOURCE}}$, 150 Ohm $Z_{\text{ANTENNA}}$

Insertion Loss $\text{dB} = 20 \log \left( \frac{Z_{\text{SOURCE}} + Z_{\text{ANTENNA}}}{Z_{\text{SOURCE}} + Z_{\text{ANTENNA}} + Z_{\text{CM}}} \right)$
• X2Y® capacitors significantly outperform CM chokes using 50Ω VNA ports
• X2Y® capacitors exhibit even greater advantage in real applications using typical 150Ω antennae.
Parasitic capacitive coupling in CM chokes results in significant mode conversion at even modest frequencies.
- Typical $\approx -35\text{dB} @ 350\text{MHz}$ ($F_{\text{KNEE}}$ IEC 61000-2-4)
- Some devices are much worse

Results in weak ESD immunity.
Differential to Common Mode Conversion Measurements

- Different chokes with the same datasheet specifications can result in dramatically different mode conversion characteristics.
- LF chokes exhibit particularly poor mode conversion at high frequencies.
Differential to Common Mode Conversion Measurements

- Ferrite beads and smaller value chokes improve mode conversion, but exhibit poorer common mode rejection
Differential to Common Mode Conversion Measurements

- **X2Y®** capacitors convert a small amount of differential energy to common mode due to finite tolerance mismatches.
- Conversion is -52dB @ 350MHz, -40dB @ 1GHz
  - 17dB better than typical CM choke / bead solution

![Measured Differential to Common Mode Conversion](image-url)
Test Comparisons

• Example, Single Board Computer Power Feed:
  – 68HC11 processor
• 5uH CM choke tested
• PI filter w/ 5uH CM choke tested
  – 0.1uF cap_5uH CM choke_220nF cap
• Seven values of X2Y® capacitors tested

• Radiated Emissions Setup:
Comparative Performance Application

- CM Choke and PI filters both exhibit similar performance
  - Filter cut-off $\approx 32\text{MHz}$
  - Attenuation effective to about $450\text{MHz}$
- Parasitic capacitance completely defeats CM choke and PI filter above $450\text{MHz}$
Comparative Performance Application

HC11 (1MHz – 500MHz, CMC and PI)

No effective attenuation
Comparative Performance Application

Slides 37-44, 50MHz –1GHz:

- X2Y® capacitors effective to 1GHz and beyond.
- Capacitance value determines low frequency rejection.
- Very small X2Y® caps (47pF) superior solution vs. CM chokes or PI filters down to 300MHz.
- 470pF and larger X2Y® caps superior over all frequencies.
Comparative Performance Application

HC11 (50MHz –1GHz, 47pF X2Y)

47pF Superior to CM choke
Above 300MHz
Comparative Performance Application

HC11 (50MHz – 1GHz, 100pF X2Y)

100pF Superior to CM choke Above 150MHz

Frequency (MHz)

dBUV

No Filter  CMC 5nH  Pi Filter  X2Y 0805 100pF  Ambient
Comparative Performance Application

HC11 (50MHz – 1GHz, 220pF X2Y)

220pF Comparable/Superior to CM choke Above 50MHz

Frequency (MHz)

dBuV

No Filter  CMC 5nH  Pi Filter  X2Y 0805 220pF  Ambient
Comparative Performance Application

HC11 (50MHz –1GHz, 330pF X2Y)

Larger X2Y® capacitor values Extend low frequency attenuation

Frequency (MHz)

dBuV

No Filter  CMC 5nH  Pi Filter  X2Y 0805 330pF  Ambient
Comparative Performance Application

HC11 (50MHz – 1GHz, 560pF X2Y)
Comparative Performance Application

HC11 (50MHz – 1GHz, 1000pF X2Y)

- dBuV vs Frequency (MHz)
- Graph showing performance comparison with different filters and ambient conditions.

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Comparative Performance Application

High frequency performance is nearly identical between capacitor values.

HC11 (50MHz –1GHz, 1000pF X2Y)
Comparative Performance Application

- **X2Y® 1000pF vastly better radiated emissions than 5uH CM choke or PI filter**
In this design, each X2Y 1206 0.1uF capacitor was used to replace a common mode choke, two resistors and two capacitors to achieve the filter results shown above.
X2Y® Capacitor Selection

• X2Y® capacitors operate as shunts.
  – Attenuate all energy above cut-off frequency
  – Select to pass required signal energy / block offensive HF noise.
  – Use capacitance value that is large enough to attenuate effectively to lowest noise frequency, but no larger than necessary.

• Four recommended selection methods:
  – 1. Pass a required signal rise / fall time.
  – 2. Pass a required signal rise / fall time as a bit interval %.
  – 3. Cut-off HF noise at a specific frequency.
  – 4. Substitute for a specific CM choke.
X2Y® Capacitor Selection Method 1.

• Use Acceptable Signal Rise and Fall Times
• Establish $T_{\text{RISE}} / T_{\text{FALL}}$
  \[ C \leq \frac{T_{\text{RISE}_{10\% - 90\% \ MIN}}}{(2.2 \times Z_{\text{SOURCE}})} \]
• Example: CAN BUS 1Mbps, 120 Ohm
  \[ T_{\text{RISE}_{10\% - 90\%}} \leq 50\text{ns} \]
  \[ Z_{\text{SOURCE}} = \frac{120 \text{ Ohms}}{2} (\text{Loosely coupled diff pair}) = 60 \text{ Ohms} \]
  \[ C_{\text{MAX}} \leq \frac{50\text{ns}}{(2.2 \times 60 \text{ Ohms})} \]
  \[ C_{\text{MAX}} \leq 380\text{pF} \]
  \[ \text{Recommended value} = 330\text{pF} \]
  \[ T_{\text{RISE}_{10\% - 90\%}} \leq 44\text{ns} \]
X2Y® Capacitor Selection Method 2.

- Pass Signal Rise and Fall Times Based on Signal Bit Rate and % Allowable $T_R / T_F$
- $T_{RISE\_10\%-90\%} / T_{FALL\_90\%-10\%} < 5\text{-}10\%$ of bit period is usually OK
  - 5%
    - $C \leq \frac{1}{(44 \times \text{Bit\_Frequency} \times Z_{\text{SOURCE}})}$
    - CAN BUS
      - $C \leq \frac{1}{(44 \times 1\text{MHz} \times 60 \text{ Ohms})} \leq 380\text{pF}$
  - 10%
    - $C \leq \frac{1}{(22 \times \text{Freq} \times Z_{\text{SOURCE}})}$
X2Y® Capacitor Selection Method 3.

- Cut Noise Down to a Specific Low Frequency
- Noise cut-off frequency $F_{CO}$ is known, source impedance $Z_{SOURCE}$ and antenna impedance $Z_{ANTENNA}$.
  - $C \Rightarrow \frac{1}{(2\pi F_{CO} (Z_{SOURCE} || Z_{ANTENNA})}$
- Example: Switching power supply harmonic suppression
  - $F_{CO} = 200$kHz
  - $Z_{SOURCE} = \text{transmission line impedance} \ 10 \ \text{Ohm}$
  - $Z_{ANTENNA} = 150 \ \text{Ohm}$
  - $C_{MIN} \geq \frac{1}{(2\pi \times 200 \text{kHz} \times 10 \ | \ | 150 \ \text{Ohm})} = 1/1.26E7 = 80\text{nF}$
  - Recommended minimum value = 100nF
- Use larger capacitances for lower frequencies and/or lower impedances.
X2Y® Capacitor Selection Method 4.

• Substitute for known CM Choke at a known source and antenna impedance:
  
  – Match choke low frequency insertion loss:
    
    • $C_{X2Y} \geq \frac{L_{CM}}{(Z_{SOURCE} \times Z_{ANTENNA})}$
    • $L_{CM}$ is the coupled inductance.
      
      – Typically ≈ 2X Inductance measured with second winding open

  – If $Z_{SOURCE}$ and/or $Z_{ANTENNA}$ are not known:
    
    • Assume 50 Ohms for $Z_{SOURCE}$
    • Assume 100 Ohms for $Z_{ANTENNA}$
    • Yields a conservative result that will perform equal or better in a real application
X2Y® Capacitor Selection Method 4.

- Example
  - 50Ω $Z_{\text{SOURCE}}$
  - 100Ω $Z_{\text{ANTENNA}}$
  - 50uH CM Choke

- \[ C_{X2Y} = \frac{50\text{uH}}{(50\Omega \times 100\Omega)} \]
  - 10nF rated value
  - 4 mil dielectric to ground

- X2Y® matches LF performance
- X2Y® provides > 20dB insertion loss improvement @ 1GHz
• Performance is typically limited by external capacitor wiring inductance:
  – L3A/L3B, L4A, L4B

• Maximize performance by minimizing L3x, and L4x inductances.
  – Follow X2Y® mounting guidelines.

• L1x, and L2x inductance is OK and even beneficial when balanced.
  – Limitation on L2 is to keep connection close to egress.
X2Y® Capacitors, Best Practices Circuit 1

- Locate capacitors close to bulkhead
- Minimize, L3A, L3B
  - Connect A, B pad connections near base of pads
- Minimize L4A, L4B:
  - Connect G1/G2 to RF return polygon on an internal PCB layer as close to the capacitor surface as possible.
    - Chassis for metal enclosures
    - Power common plane for plastic enclosures.
    - 12mil vs 4mil upper dielectric costs about 3dB insertion loss @1GHz
  - Metal enclosures attach RF return polygon to chassis w/ low inductance
    - Multiple attachments along PCB edge recommended
Example X2Y® Layout
Low L3x, L4x

Connect G1/G2 to RF Return Polygon
Locate the RF Return Polygon On A Layer as Close to the Capacitor Surface as Possible

Enclosure Bulkhead

Minimize RF Return Polygon Attachment Inductance to Enclosure (Metallic Enclosures Only)

Run A/B Traces Close to Pad Inner Edges

Center Pad May Be Split Into Separate G1/G2 Pads

Locate Capacitor Close to Enclosure Bulkhead

RF Return Polygon Chassis Connection (Metallic Enclosure) Or Power Common (Plastic Enclosure)
X2Y® Capacitors, Mounting Errors

Example, Circuit 1 Mount:

- **AVOID THESE BAD PRACTICES:**
  - “T” to A, or B pad connections
  - Leaving G2 unconnected
  - Stringer trace from any pad.

- Any of the above practices insert substantial inductance which impairs performance at high frequency.
Summary

• Most EMI problems are Common Mode.
• Reduce common mode by attenuating driving voltage and/or mismatching antenna impedance.
  – Properly mounted X2Y® caps do both
• Series elements suffer from mode conversion and/or poor CM insertion loss at high frequencies.
• X2Y® capacitors maintain good CM insertion loss and mode conversion figures into the GHz.
Summary

• Magnetics noise suppression degrades as actual circuit antenna impedance increases above measuring instrument 50Ω impedance.
  – Real w/150Ω antenna is typically 3dB worse than 50Ω VNA measurement

• X2Y® noise suppression improves as actual circuit antenna impedance increases above measuring instrument 50Ω impedance.
  – Real w/150Ω antenna is 3dB better than 50Ω VNA

• X2Y® capacitor values may be easily selected to filter EMI based on any:
  – Required signal pass-band (sets max capacitor value),
  – Required noise stop-band (sets min capacitor value),
  – Improved replacement for existing CM magnetics
Summary

- **X2Y®**
  - Small, Light
  - Lower Cost
  - Higher Reliability
  - Lowest Assembly Cost
  - Superior HF Performance

- **CM Choke**
  - Large, Heavy
  - Expensive
  - Subject To Vibration Induced Failure
  - Poor HF Performance