Reconfigurable RF CMOS Circuits for Cognitive Radios

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Outline

• Roadmap for multi-standard RFIC
• Rx requirements
  – Linearity & NF
• LO requirements
  – Q and $V_{DD}$
  – Frequency tuning range
  – Multiband VCO results
• Tx requirements
  – Tunable PA results
• Conclusion
Motivation

Demand for a multi-standard RFIC
- Frequency range from 400MHz to 6GHz
- Smaller footprint
- Smaller number of components with competitive sensitivity and $P_{dc}$
# Multi-standard radio roadmap

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<th>Future</th>
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<td>NF &lt; 2.2dB (2.5dB total)</td>
<td>400MHz-6GHz NF &lt; 2dB</td>
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<td>IIP3 &gt; 0dBm w/o SAW filter</td>
<td>IIP3 &gt; 0dBm with tunable BPF/BRF</td>
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<td>IIP2 &gt; 40dBm</td>
<td>IIP2 &gt; 60dBm</td>
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<td>IIP2 &gt; 60dBm</td>
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<td>Reduced off-chip PAs, Reduced off-chip matching</td>
<td>On-chip multi-standard PA</td>
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<td>Reduced off-chip PAs, Reduced off-chip matching</td>
<td>Off-chip multi-standard PAs</td>
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<tr>
<td></td>
<td>Reduced off-chip matching</td>
<td>Off-chip multi-standard PA</td>
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<td>Reduced off-chip matching</td>
<td>Off-chip multi-standard PA</td>
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<tr>
<td><strong>LO</strong></td>
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<tr>
<td></td>
<td>GSM</td>
<td>-185dBc/Hz(FoM) no spurs, GSM</td>
</tr>
<tr>
<td></td>
<td>GSM</td>
<td>-190dBc/Hz(FoM) no spurs, GSM</td>
</tr>
<tr>
<td></td>
<td>Reduced multiple PLLs</td>
<td>400MHz-6GHz with 1 inductor</td>
</tr>
<tr>
<td></td>
<td>Multiple PLLs</td>
<td>400MHz-6GHz with 1 inductor</td>
</tr>
</tbody>
</table>

*Lower NF/sensitivity is required for some commercial applications.*
The present multi-standard RFIC

QUALCOMM RTR6285

- UMTS 9 bands with diversity
- GSM/EDGE 4 bands
- GPS 1 band

from datasheet
The near-future multi-standard RFIC

- Smaller number of IO pins and external components
  - A single-ended input is better.
- HB Rx(1.8-2.1GHz) should be combined without SAW filters.
  - NF < 2.2dB, IIP3 > -2.5dBm, IIP2 > 70dBm
- GSM bands should also be combined.
- Handling of UMTS/LTE bands 7 and 11
- Must keep the same sensitivity with smaller area and smaller power consumption
One-chip Reconfigurable RFIC

- All cellular, WLAN/WPAN, and broadcast services should be covered.
- On-chip tunable Tx/Rx filters optimized for some particular bands
- On/off-chip tunable/switchable multi-standard PA
- External switchable duplexers are utilized for each FDD standard.
One-chip full Reconfigurable RFIC

- Equally designed for every bands
- Just advancement of NF and linearity improvement with tunable on-chip filters for possible interferers
- On/off-chip tunable/switchable multi-standard PA
- Without special optimization for particular bands
- Possibly, external switchable duplexers/SW are still required.
- Seamless TDD/FDD reconfiguration
- Reconfigurablity is required for RF/ABB
- Much smaller frequency step
- Cognition time (RF assisted)
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  – Q and $V_{DD}$
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  – Tunable PA results
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**Rx requirements**

- Linearity is very important for FDD systems like UMTS.
- Tx signal leaks into Rx path, and it becomes a very large interferer.
- Linearity is also very important, especially for concurrent operation of multiple on-chip transceivers.
On-Chip PA-to-LNA isolation

Must consider isolation between on-chip RF blocks for concurrent operation of multiple front-ends
Requirements for SAW-less UMTS Rx

- PG=15dB
- NF=2.2dB
- IIP3=0dBm

-20dB@Tx

- PG=10dB
- NF=6dB
- IIP3=6.1dBm
- IIP2=30dBm

for out-of-band

PG=15dB
NF=2.2dB
IIP3=0dBm

PG=10dB
NF=6dB
IIP3=16.1dBm
IIP2=70dBm

for out-of-band

REFSENS=-110dBm
PG=25dB
IIP3=-2.5dBm
IIP2=70dBm
NF=2.5dB (3dB total)
Dup.loss=3dB
with

PTx=-30dBm
P_{CW\_inter}=-40dBm
P_{CW\_out}=-60dBm

from Panasonic
Required IIP3 for SAW-less mixer

\[ \text{IIP3} \text{ of } -2.5\text{dBm is required for the entire Rx chain.} \]

**Graph:**
- **Mixer IIP3 [dBm]**
- **LNA IIP3 [dBm]**
- **SAW-less**
- **-10dB ATT.@Tx**
- **-20dB ATT.@Tx**

**Equation:**
\[ \text{IIP3}_{\text{total}} + P_{\text{GLNA}} = 12.5\text{dBm} \]

**Parameters:**
- \( P_{\text{GLNA}} = 15\text{dB} \)
Requirements for multi-standard Rx

Some kind of reconfiguration is required. On-chip tunable filter is indispensable.

Rx
- Band width 400MHz-6GHz
  - GSM/UMTS/LTE, GPS, WLAN, BT, DTV/FM, etc
- Rx NF <2.5dB for Cellular, IIP3 >-2.5dBm for UMTS
- Rx NF <2dB for GPS

LNA
- IIP3 >0dBm
- NF <2.2dB
- PG = 15dB

Mixer (with LNA of PG=15dB, NF=2.2dB, IIP3=0dBm)
- NF <6dB
- IIP3 >16.1dBm without inter-stage filter
- IIP2 >70dBm without inter-stage filter
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LO requirements

• 10MHz-10GHz continuous tuning
• Low phase noise
  GSM850/900 -162dBc/Hz@20MHz-offset
  Q of on-chip inductor < 15
  Supply voltage <1.5V
• No spurs
• Quadrature outputs with less I/Q mismatch
• Low power consumption
• Small layout area
  smaller number of on-chip inductors
VCO topologies

(1) NMOS VCO  (2) CMOS VCO  (3) Class-C VCO*

*A. Mazzanti and P. Andreani, JSSC 2008
Theoretical limit of phase noise

NMOS VCO can realize the lowest phase noise theoretically.

\[ PN = 10 \log_{10} \left( \frac{\omega^3}{\Delta \omega^2} \frac{L}{Q} \frac{k_B T (1 + \gamma_n)}{4 V_{DD}^2} \right) \]
Limited Q-factor

Inductor

\[ Q_L = \frac{\omega}{2} \left| \frac{1}{Z} \frac{\partial Z}{\partial \omega} \right|_{\omega=\omega_0} \]

Switched cap.

QL (0.64nH)
QL (1.3nH)
QL (3.4nH)

Qc (65nm)
Qc (180nm)
Q-factor of LC tank

5GHz-to-15GHz is better to obtain a high-Q LC resonator.
Supply voltage issues

- VCO Phase Noise
- LNA Linearity, PA Pout

\[ \begin{align*}
PN &= 10 \log_{10} \left( \frac{\omega^3}{\Delta \omega^2} \frac{L}{Q} \frac{k_B T}{4V_{dd}^2} \left(1 + \gamma_n\right) \right)
\end{align*} \]

Power supply for a mobile RFIC

Battery \[3.6V\] DC-DC conv. \[1.8V\] LDO 1.2V for digital LDO 1.2V for digital

Noisy

>0.3V drop

<1.5V for RF
## Required supply voltage for GSM

### GSM900 Tx LO: -165dBc/Hz@20MHz-offset

<table>
<thead>
<tr>
<th>Qtank</th>
<th>VDD [V]</th>
<th>Ideal PN [dBc/Hz] +5dB @0.9GHz</th>
<th>Required Ibias [mA]</th>
<th>Pdc [mW]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Q=9 (L=3.4nH) @3.6GHz</td>
<td>1.2</td>
<td>-162</td>
<td>7.8</td>
<td>14.1+α</td>
</tr>
<tr>
<td></td>
<td>1.5</td>
<td>-164</td>
<td>7.8</td>
<td>14.1+α</td>
</tr>
<tr>
<td>Q=12 (L=1.3nH) @7.2GHz</td>
<td>1.2</td>
<td>-164</td>
<td>5.8</td>
<td>10.5+α</td>
</tr>
<tr>
<td></td>
<td>1.5</td>
<td>-166</td>
<td>5.8</td>
<td>10.5+α</td>
</tr>
<tr>
<td>Q=30 (ext.) (L=1.3nH) @7.2GHz</td>
<td>1.2</td>
<td>-168</td>
<td>1.5</td>
<td>2.7+α</td>
</tr>
<tr>
<td></td>
<td>1.5</td>
<td>-170</td>
<td>1.5</td>
<td>2.7+α</td>
</tr>
</tbody>
</table>

VCO cannot reach with low digital VDD.
LO generation for GSM/UMTS/LTE

Conventional approach:

- Frequency bands:
  - 824-960 MHz
  - 1710-2170 MHz
  - 3296-4340 MHz or 2x

- Bands labeled:
  - Band 1
  - Band 2
  - Band 3
  - Band 4
  - Band 5
  - Band 6
  - Band 7
  - Band 8
  - Band 9
  - Band 10
  - Band 11

- Regions marked:
  - Band 7
  - Band 11

- Markings indicate:
  - Rx (Receive) and Tx (Transmit)
Requirements for multi-standard LO

• Satisfy all existing/possible wireless standards
• 10MHz-6GHz continuous tuning with 1 inductor
• Fine tuning and fast settling for cognitive radios
• Low phase noise (GSM850/900)
• No spurs for wideband RF signal
• Quadrature outputs with less I/Q mismatch
• Low power consumption <10mW
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  – Multi-band VCO results
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Previous work for multi-band VCO

- **Switched-Capacitor Resonator**
  - + Reduced $K_{VCO}$
  - - $QL$ is degraded at edge of tuning range
  - - Limited $C_{\text{max}}/C_{\text{min}}$ (parasitic capacitance limited)

- **1/2 Divider**
  - + Continuous wide tuning range
  - - Wide tuning range requirement for VCO
  - - Poor phase noise

- **Dividers, Mixers**
  - + Small area
  - - Large power consumption
  - - Spurious tones

Proposed wideband VCO

Core-VCO
8 to 12 GHz
$f_{max}/f_{min} = 1.5$
Differential

Injection-Locked Frequency Divider (ILFD)
1.33 to 6 GHz
$f_{max}/f_{min} = 4.5$
Quadrature

Narrow required tuning range, No spur, Quadrature output

*S. Hara, et al., A-SSCC 2009
Circuit schematics

- ILFD generates 1.33 to 6.0 GHz output.
- Lower frequency (under 1.33GHz) can be obtained by using FF dividers.
Impulse Sensitivity Function (ISF*)

Voltage Waveform

Case 1

Case 2

Phase is NOT shifted

Phase is shifted

ISF

*A.Hajimiri, and T.Lee, JSSC 1998
Ideal Current Conduction

Ideal Current

Conventional LC-VCO
Current conduction of class-C VCOs

Ideal Current

Class-C VCO
Class-C VCO

\[ V_{\text{eff}} = V_{gs} - V_{\text{th}} \]

Conventional LC-VCO

\[ V_{\text{eff}} = V_{gs} - V_{\text{th}} \]

Class-C VCO

*A. Mazzanti, et al., JSSC 2008*
Current conduction of class-C VCOs

Class-C VCO

Tail-Feedback VCO
Tail-feedback VCO

Tail feedback
3.5dB phase noise improvement

- Tuning range: 8.0 to 12.0 GHz
Injection Locked Frequency Divider

2-stage differential ILFD is utilized.
Tuning range: 1.3 to 6.0 GHz
Merit: Quadrature output, No Spur, Wide frequency range
Measurement Result

Fabricated by 90 nm CMOS Process
Output spectrum

Even harmonics can be canceled by differential config. Odd harmonics can be canceled by harmonic-rejection mixer.
## VCO performance

<p>| | |</p>
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<tr>
<td><strong>Technology</strong></td>
<td>Standard 90nm CMOS</td>
</tr>
<tr>
<td><strong>Supply voltage</strong></td>
<td>1.2 V</td>
</tr>
<tr>
<td><strong>Power consumption of VCO core</strong></td>
<td>4.8 - 10.2 mW</td>
</tr>
<tr>
<td><strong>Power consumption of ILFD</strong></td>
<td>1.0 - 1.3 mW</td>
</tr>
<tr>
<td><strong>Power consumption of FF dividers</strong></td>
<td>- 0.1 mW</td>
</tr>
<tr>
<td><strong>Total power consumption</strong></td>
<td>5.9 - 11.2 mW</td>
</tr>
<tr>
<td><strong>Tuning range</strong></td>
<td>9.3 MHz - 5.7 GHz</td>
</tr>
<tr>
<td><strong>Chip area</strong></td>
<td>250 μm x 200 μm</td>
</tr>
</tbody>
</table>
## VCO measurement summary

<table>
<thead>
<tr>
<th></th>
<th>This work*</th>
<th>VLSI 2009**</th>
<th>RFIC 2009***</th>
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</thead>
<tbody>
<tr>
<td><strong>Architecture</strong></td>
<td>VCO with ILFD</td>
<td>QVCO with mixer and dividers</td>
<td>2VCOs and dividers</td>
</tr>
<tr>
<td><strong>Divide ratio</strong></td>
<td>2,3,4,6…</td>
<td>2,3,4,5,6,8,10</td>
<td>2,4,8,16,32…</td>
</tr>
<tr>
<td><strong>Tuning range of core LC-VCO</strong></td>
<td>±20 %</td>
<td>±20 %</td>
<td>±33.3 % (total)</td>
</tr>
<tr>
<td><strong>Output freq.</strong></td>
<td>0.009 - 5.7 GHz</td>
<td>1 - 10 GHz</td>
<td>0.1 - 5.0 GHz</td>
</tr>
<tr>
<td><strong>Power cons.</strong></td>
<td>5.9 - 11.2 mW</td>
<td>31 mW</td>
<td>19.8 mW</td>
</tr>
<tr>
<td><strong>FoMT</strong></td>
<td>-210 dBc/Hz</td>
<td>-194 dBc/Hz</td>
<td>-209 dBc/Hz</td>
</tr>
<tr>
<td><strong>Area</strong></td>
<td>0.05 mm²</td>
<td>0.29 mm²</td>
<td>0.22 mm²</td>
</tr>
</tbody>
</table>

* *S. Hara, et al., A-SSCC, Nov. 2009*

** *B. Razavi, VLSI Circuits, June 2009.*

*** *P. Nuzzo, et al., RFIC, June 2009.*
Summary and Conclusion

- A differential LC-VCO and injection locked frequency divider are utilized instead of a QVCO and SSBMs to reduce spurious, layout area, and power consumption.
- The proposed wideband VCO can achieve wide tuning range with the best FoM\(_T\).

FTR=199% (9.3MH-5.7GHz)
FOM\(_T\)=−210dBc/Hz
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Tx requirements

- On/off-chip tunable/switchable multi-standard PA
- Must keep the same Pout/PAE with smaller total footprint size and less number of components

Present

Future

tunable/switchable
Challenge of tunable CMOS PA

- Tunable CMOS PA with tunable impedance matching to reduce external components
  - Isolators
    - Reduce reflection due to impedance mismatch
    - Protect PAs from reflected wave

Conventional

Proposed
Output impedance tuning 1

If \( r_{ds} = \infty \),

\[
Z_{out} = \frac{R_f + R_s}{g_m R_s + 1} \parallel \frac{1}{j \omega C} \parallel (R_L + j \omega L)
\]

When \( f = \frac{1}{2 \pi \sqrt{LC}} \)

(Resonance frequency)

\[
Z_{out} = \frac{R_f + R_s}{g_m R_s + 1} \parallel \frac{L}{CR_L}
\]

Tune C to cancel imaginary part of \( Z_{out} \) at arbitrary frequency

\( R_s \): source impedance (50 \( \Omega \))

\( R_L \): inductor parasitic resistance
Output impedance tuning 2

\[ Z_{out} = \frac{R_f + R_s}{g_m R_s + 1} \parallel \frac{L}{CR_L} \]

- Tune \( R_f \) to match \( Z_{out} \) to 50 \( \Omega \)
- \( Z_{out} \) depends on the value of \( C \), so \( R_f \) needs to be adjusted according to the matching frequency

Casceded thick-oxide transistors are utilized because of larger \( r_{ds} \) and voltage-stress robustness.

\( R_s \): source impedance (50 \( \Omega \))
\( R_L \): inductor parasitic resistance
Schematic of the proposed PA

- Change output matching band by switching C and R
- Differential topology for 3dB larger $P_{\text{sat}}$

$V_{\text{DD}}=3.3V$
Voltage stress of switches

- Maximum voltage swing at output node is about $V_{DD}=3.3V$
- The same voltage is applied to switches when they are off

Thick oxide nMOS is applied as a switch
Switch biasing

- Large voltage swing makes an off-state switch turned on for a moment
- Degrade large signal characteristics such as $P_{1\text{dB}}$

Bias to source and drain of off-state switches

![Diagram of switch biasing](image)
Simulation of switch biasing effect

Off-state switches start to be turned on

Graph showing Pout [dBm] vs Pin [dBm]

- P1dB = 22 dBm
- P1dB = 13 dBm
Chip micrograph[7]

- 0.18\(\mu\)m CMOS
- Chip was measured using probes and external DC block capacitors
Small signal S-parameters

- Differential mode S-parameter calculated from 4-port S-parameter

Solid line: Simulation
Marker: Measurement

0.9~3.0GHz, $S_{22} < -10$dB, $S_{21} > 16$dB
P_{out}, PAE v.s. Frequency

- Measured large signal performance in each band and each signal frequency

- $P_{sat}$ is larger than 19dBm, and PAE@peak is larger than 11% at the entire frequency range
## Comparison of CMOS PAs

<table>
<thead>
<tr>
<th>Tech.</th>
<th>V\textsubscript{DD} [V]</th>
<th>Freq. [GHz]</th>
<th>P\textsubscript{sat} [dBm]</th>
<th>PAE@peak [%]</th>
<th>Area [mm\textsuperscript{2}]</th>
<th>Output matching</th>
</tr>
</thead>
<tbody>
<tr>
<td>RFIC ’04 [3]</td>
<td>0.13\textmu m CMOS</td>
<td>2.0</td>
<td>2.0 ~ 8.0</td>
<td>7 ~ 10</td>
<td>2 (@1dB)</td>
<td>—</td>
</tr>
<tr>
<td>ISSCC ’09 [4]</td>
<td>0.13\textmu m CMOS</td>
<td>1.5</td>
<td>0.5 ~ 5.0</td>
<td>14 ~ 21</td>
<td>3 ~ 16 (drain eff.)</td>
<td>3.6</td>
</tr>
<tr>
<td>T-MTT ’07 [5]</td>
<td>0.18\textmu m CMOS</td>
<td>2.8</td>
<td>3.7 ~ 8.8</td>
<td>16 ~ 19</td>
<td>8 ~ 25</td>
<td>2.8</td>
</tr>
<tr>
<td>ISSCC ‘09 [6]</td>
<td>0.13\textmu m CMOS</td>
<td>3.0</td>
<td>1.0 ~ 2.5</td>
<td>28 ~ 31</td>
<td>18 ~ 43</td>
<td>2.56*</td>
</tr>
<tr>
<td>This work [7]</td>
<td>0.18\textmu m CMOS</td>
<td>3.3</td>
<td>0.9 ~ 3.0</td>
<td>20 ~ 22</td>
<td>11 ~ 23</td>
<td>1.03</td>
</tr>
</tbody>
</table>

*With distributor
Summary & Conclusion

- The first tunable CMOS PA utilizing a feedback technique
- 0.9-3.0 GHz output matching
- At the entire frequency range, over 19dBm output power and over 11% PAE is achieved
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Conclusion

Rx

- NF and linearity trade-off is very tough for realizing a full-SDR/CR. A new idea is still required.
- Some kind of reconfiguration is required to satisfy various requirements for every wireless standards.
  - Linearity, Noise, Power consumption, etc
- We should also pay attention to the research trend of external components, e.g., duplexer, antenna, SW, etc.

Tx
- Tunablity is required.

LO
- There are some ways, but it is still challenging.
References

VCO


PA


References


Rx


References


Appendix
### 3GPP standard (GSM/UMTS/LTE)

<table>
<thead>
<tr>
<th>E-UTRA Operating Band</th>
<th>Uplink (UL) operating band BS receive UE transmit $F_{UL_{low}} - F_{UL_{high}}$</th>
<th>Downlink (DL) operating band BS transmit UE receive $F_{DL_{low}} - F_{DL_{high}}$</th>
<th>Duplex Mode</th>
<th>Tx-Rx separation</th>
<th>Band width</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 1920 MHz – 1980 MHz</td>
<td>2110 MHz – 2170 MHz</td>
<td>FDD 190 MHz 60 MHz</td>
<td>UMTS2100 (Japan)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2 1850 MHz – 1910 MHz</td>
<td>1930 MHz – 1990 MHz</td>
<td>FDD 80 MHz 60 MHz</td>
<td>PCS/DCS1900(region2 North America)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3 1710 MHz – 1785 MHz</td>
<td>1805 MHz – 1880 MHz</td>
<td>FDD 95 MHz 75 MHz</td>
<td>DCS/GSM1800 (EU, China, etc)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4 1710 MHz – 1755 MHz</td>
<td>2110 MHz – 2155 MHz</td>
<td>FDD 400 MHz 45 MHz</td>
<td>UMTS1.7/2.1 (AWS, region 2)</td>
<td></td>
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<td></td>
</tr>
<tr>
<td>5 824 MHz – 849 MHz</td>
<td>869 MHz – 894 MHz</td>
<td>FDD 45 MHz 25 MHz</td>
<td>UMTS850 (GSM850, region 2)</td>
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<tr>
<td>6 830 MHz – 840 MHz</td>
<td>875 MHz – 885 MHz</td>
<td>FDD 45 MHz 10 MHz</td>
<td>UMTS800 (Japan)</td>
<td></td>
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<tr>
<td>7 2500 MHz – 2570 MHz</td>
<td>2620 MHz – 2690 MHz</td>
<td>FDD 120 MHz 70 MHz</td>
<td>UMTS2600 (North America)</td>
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<tr>
<td>8 880 MHz – 915 MHz</td>
<td>925 MHz – 960 MHz</td>
<td>FDD 45 MHz 35 MHz</td>
<td>UMTS900 (E-GSM900) (EU, China, etc)</td>
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<tr>
<td>9 1749.9 MHz – 1784.9 MHz</td>
<td>1844.9 MHz – 1879.9 MHz</td>
<td>FDD 95 MHz 35 MHz</td>
<td>UMTS1700 (Japan)</td>
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<tr>
<td>10 1710 MHz – 1770 MHz</td>
<td>2110 MHz – 2170 MHz</td>
<td>FDD 400 MHz 60 MHz</td>
<td>Extended UMTS1.7/2.1 (region 2)</td>
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<tr>
<td>11 1427.9 MHz – 1452.9 MHz</td>
<td>1475.9 MHz – 1500.9 MHz</td>
<td>FDD 48 MHz 25 MHz</td>
<td>UMTS1500 (Japan, PDC1500)</td>
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<tr>
<td>12 698 MHz – 716 MHz</td>
<td>728 MHz – 746 MHz</td>
<td>FDD 30 MHz 18 MHz</td>
<td>TBD</td>
<td></td>
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<tr>
<td>13 777 MHz – 787 MHz</td>
<td>746 MHz – 756 MHz</td>
<td>FDD -31 MHz 10 MHz</td>
<td>TBD</td>
<td></td>
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<tr>
<td>14 788 MHz – 798 MHz</td>
<td>758 MHz – 768 MHz</td>
<td>FDD -30 MHz 10 MHz</td>
<td>TBD</td>
<td></td>
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<tr>
<td>...</td>
<td>704 MHz – 716 MHz</td>
<td>734 MHz – 746 MHz</td>
<td>FDD 30 MHz 12 MHz</td>
<td>TBD</td>
<td></td>
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<tr>
<td>17 815 MHz – 830 MHz</td>
<td>860 MHz – 875 MHz</td>
<td>FDD 45 MHz 15 MHz</td>
<td>TBD</td>
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<tr>
<td>18 830 MHz – 845 MHz</td>
<td>875 MHz – 890 MHz</td>
<td>FDD 45 MHz 15 MHz</td>
<td>TBD</td>
<td></td>
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<tr>
<td>...</td>
<td>1900 MHz – 1920 MHz</td>
<td>1900 MHz – 1920 MHz</td>
<td>TDD 20 MHz</td>
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<tr>
<td>33 2010 MHz – 2025 MHz</td>
<td>2010 MHz – 2025 MHz</td>
<td>TDD 15 MHz</td>
<td></td>
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<tr>
<td>34 1850 MHz – 1910 MHz</td>
<td>1850 MHz – 1910 MHz</td>
<td>TDD 60 MHz</td>
<td></td>
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<tr>
<td>35 1930 MHz – 1990 MHz</td>
<td>1930 MHz – 1990 MHz</td>
<td>TDD 60 MHz</td>
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<tr>
<td>36 1910 MHz – 1930 MHz</td>
<td>1910 MHz – 1930 MHz</td>
<td>TDD 20 MHz</td>
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<tr>
<td>37 2570 MHz – 2620 MHz</td>
<td>2570 MHz – 2620 MHz</td>
<td>TDD 50 MHz</td>
<td></td>
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<tr>
<td>38 1880 MHz – 1920 MHz</td>
<td>1880 MHz – 1920 MHz</td>
<td>TDD 40 MHz</td>
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<td>39 2300 MHz – 2400 MHz</td>
<td>2300 MHz – 2400 MHz</td>
<td>TDD 100 MHz</td>
<td></td>
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<td>40 ...</td>
<td>2400 MHz – 2400 MHz</td>
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</tbody>
</table>

### 3GPP TS 36.101, v9.1.0, 2009-09 + GPS, DTV, WLAN, Bluetooth

**Notes:**
- **Fx:** Frequency band
- **Tx-Rx separation:** Transmission-reception separation
- **Bandwidth:** Bandwidth of the operating band
- **Duplex Mode:** Duplex mode
- **BS transmit:** Base station transmit
- **BS receive:** Base station receive
- **UE transmit:** User equipment transmit
- **UE receive:** User equipment receive
- **FDD:** Frequency division duplex
- **TDD:** Time division duplex
- **TBD:** To be determined
### Theoretical limit of phase noise

<table>
<thead>
<tr>
<th></th>
<th>NMOS VCO</th>
<th>CMOS VCO</th>
<th>Class-C VCO</th>
</tr>
</thead>
<tbody>
<tr>
<td>$v_{out+}, v_{out-}$</td>
<td>$0 \sim 2V_{DD}$</td>
<td>$0 \sim V_{DD}$</td>
<td>$V_{DD} \pm \frac{V_{DD} + V_{od}}{1+k}$</td>
</tr>
<tr>
<td>$v_{sig}$</td>
<td>$R_p i_{sig}$</td>
<td>$R_p i_{sig}$</td>
<td>$R_p i_{sig}$</td>
</tr>
<tr>
<td>$i_{sig}$</td>
<td>$\frac{2}{\pi} I_{bias} \sin \omega t$</td>
<td>$\frac{4}{\pi} I_{bias} \sin \omega t$</td>
<td>$I_{bias} \sin \omega t$</td>
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<tr>
<td>I-limit</td>
<td>$I_{bias} &lt; \frac{\pi V_{DD}}{R_p}$</td>
<td>$I_{bias} &lt; \frac{\pi V_{DD}}{4R_p}$</td>
<td>$\frac{V_{od}}{kR_p} &lt; I_{bias} &lt; \frac{V_{DD} + V_{od}}{(1+k)R_p}$</td>
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<tr>
<td>$P_{sig(I \text{ region})}$</td>
<td>$\frac{2R_p I_{bias}^2}{\pi^2}$</td>
<td>$\frac{8R_p I_{bias}^2}{\pi^2}$</td>
<td>$\frac{R_p I_{bias}^2}{2}$</td>
</tr>
<tr>
<td>$P_{sig(V \text{ region})}$</td>
<td>$\frac{2V_{DD}^2}{R_p}$</td>
<td>$\frac{V_{DD}}{2R_p}$</td>
<td>---</td>
</tr>
<tr>
<td>$P_{sig(max)}$</td>
<td>$\frac{2V_{DD}^2}{R_p}$</td>
<td>$\frac{V_{DD}}{2R_p}$</td>
<td>$\frac{1}{2R_p} \left( \frac{V_{DD} + V_{od}}{1+k} \right)^2$</td>
</tr>
<tr>
<td>$PN_{(I \text{ region})}$</td>
<td>$\frac{f_0^2}{\Delta f^2} \frac{k_B T}{Q^2} \frac{\pi^2 (1+\gamma_N)}{4R_p I_{bias}^2}$</td>
<td>$\frac{f_0^2}{\Delta f^2} \frac{k_B T}{Q^2} \frac{\pi^2 (1+\gamma_N+\gamma_P)}{16R_p I_{bias}^2}$</td>
<td>$\frac{f_0^2}{\Delta f^2} \frac{k_B T}{Q^2} \frac{(1+\gamma_N)}{2R_p I_{bias}^2}$</td>
</tr>
<tr>
<td>$PN_{(V \text{ region})}$</td>
<td>$\frac{f_0^2}{\Delta f^2} \frac{k_B T}{Q^2} \frac{(1+\gamma_N)R_p}{4V_{DD}^2}$</td>
<td>$\frac{f_0^2}{\Delta f^2} \frac{k_B T}{Q^2} \frac{(1+\gamma_N+\gamma_P)R_p}{V_{DD}^2}$</td>
<td>---</td>
</tr>
<tr>
<td>$PN_{(min)}$</td>
<td>$\frac{f_0^2}{\Delta f^2} \frac{k_B T}{Q^2} \frac{(1+\gamma_N)R_p}{4V_{DD}^2}$</td>
<td>$\frac{f_0^2}{\Delta f^2} \frac{k_B T}{Q^2} \frac{(1+\gamma_N+\gamma_P)R_p}{V_{DD}^2}$</td>
<td>$\frac{f_0^2}{\Delta f^2} \frac{k_B T}{Q^2} \frac{(1+\gamma_N)R_p (1+k)^2}{2(V_{DD} + V_{od})^2}$</td>
</tr>
<tr>
<td>$FoM_{(I \text{ region})}$</td>
<td>$\frac{10^3 k_B T}{Q^2} \frac{\pi^2 (1+\gamma_N) V_{DD}}{4R_p I_{bias}}$</td>
<td>$\frac{10^3 k_B T}{Q^2} \frac{\pi^2 (1+\gamma_N+\gamma_P) V_{DD}}{16R_p I_{bias}}$</td>
<td>$\frac{10^3 k_B T}{Q^2} \frac{(1+\gamma_N) V_{DD}}{2R_p I_{bias}}$</td>
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<tr>
<td>$FoM_{(V \text{ region})}$</td>
<td>$\frac{10^3 k_B T}{Q^2} \frac{(1+\gamma_N) R_p I_{bias}}{4V_{DD}}$</td>
<td>$\frac{10^3 k_B T}{Q^2} \frac{(1+\gamma_N+\gamma_P) R_p I_{bias}}{V_{DD}}$</td>
<td>---</td>
</tr>
<tr>
<td>$FoM_{(min)}$</td>
<td>$\frac{10^3 k_B T}{Q^2} \frac{\pi (1+\gamma_N)}{4}$</td>
<td>$\frac{10^3 k_B T}{Q^2} \frac{\pi (1+\gamma_N+\gamma_P)}{4}$</td>
<td>$\frac{10^3 k_B T}{Q^2} \frac{(1+\gamma_N) (1+k) V_{DD}}{2(V_{DD} + V_{od})}$</td>
</tr>
</tbody>
</table>