Picasso:
Flexible RF and Spectrum Slicing

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Problem

Protocol heterogeneity and density is causing unlicensed spectrum fragmentation.
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Protocol heterogeneity and density is causing *unlicensed spectrum fragmentation*

Coexisting networks share arbitrary fragments of available spectrum which vary in time and space
What would we want?

Will not work with legacy 802.11 PHY
What would we want?

Will not work with legacy 802.11 PHY
What would we want?

2.4 GHz

Frequency

2.5 GHz
What would we want?

Need to transmit and receive simultaneously to support legacy 802.11 MAC.
What would we want?

Objective: Transmit and Receive Simultaneously over Arbitrary Bands with a Single Antenna/RF Frontend
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Objective: Transmit and Receive Simultaneously over Arbitrary Bands with a Single Antenna/RF Frontend
More than just fragment exploitation

- Current practice is to use a separate radio and antenna for each protocol.
- Portable device real estate is limited, increasingly difficult to pack antennas

Such an ability could also be used for radio sharing and coexistence
Picasso Contributions

- System which flexibly slices the radio/antenna and spectrum

- Runs decoupled basebands which can TX/RX independently with arbitrary bandwidths
What do we mean by decoupling?

Case 1: TX/TX
What do we mean by decoupling?

Single Shared Antenna/RF Frontend

**Picasso: RF and Spectrum Slicing Layer**

- WiFi 1
- WiFi 2
- ZigBee
- Bluetooth

Case 1: TX/TX
What do we mean by decoupling?

TX
\[ f_1 \]

\[ f_2 \] 2.45GHz \[ f_3 \] \[ f_4 \]

**Single Shared Antenna/RF Frontend**

**DAC**

**ADC**

*Picasso: RF and Spectrum Slicing Layer*

*WiFi 1*  
*WiFi 2*  
*ZigBee*  
*Bluetooth*

**Case 1:**  
TX/TX

**Case 2:**  
RX/RX
What do we mean by decoupling?

Single Shared Antenna/RF Frontend

**Picasso: RF and Spectrum Slicing Layer**

- **Case 1:** TX/TX
- **Case 2:** RX/RX
What do we mean by decoupling?

**Picasso: RF and Spectrum Slicing Layer**

- **Case 1:** TX/TX
- **Case 2:** RX/RX
- **Case 3:** TX/RX
What do we mean by decoupling?

**Diagram:**
- Single Shared Antenna/RF Frontend
- Picasso: RF and Spectrum Slicing Layer
- DAC
- ADC
- WiFi 1
- WiFi 2
- ZigBee
- Bluetooth

**Cases:**
- Case 1: TX/TX
- Case 2: RX/RX
- Case 3: TX/RX
Why can’t the radio Tx/Rx simultaneously?

- TX signal is 100dB + stronger than RX signal
- Typically filter in analog prior to sampling
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Why can’t the radio Tx/Rx simultaneously?

- TX signal is 100dB + stronger than RX signal
- Typically filter in analog prior to sampling

Fixed analog filters are inadequate because the spectrum fragments vary in space and time
Receiver Saturation

Analog Self Interference

Analog Received Signal

Transceiver Block Diagram

Tx
DAC
LNA/LO
ADC
Rx
Receiver Saturation

Analog Self Interference

Analog Received Signal

Transceiver Block Diagram

Tx

DAC

Self Interference Cancellation

LNA/LO

ADC

Rx
Receiver Saturation

Analog Self Interference

Analog Received Signal

Transceiver Block Diagram

Tx

Self Interference Cancellation

DAC

LNA/LO

Rx

ADC
Can we achieve enough cancellation to prevent receiver saturation?
How much cancellation is required?

**Receiver**

-85dBm

Weakest RX SNR = 5dB

-4dBm

14-bit ADC DR = 86dB

**Transmitter**

Max Tx Power +30dBm

Minimum Cancellation = 45dB

-15dBm (Preserves >10dB margin from point of Receiver Saturation)

Thermal Noise Floor -90dBm

For 14-bit ADCs, Picasso requires approximately **45dB** of cancellation
Recent Full Duplex Work

A) Active (QHX) Balun Cancellation [Mobicom’11]

Balun (Used as signal inverter)

QHX220

Dynamic Cancellation Loop

Received Signal Power (dBm)

-120
-100
-80
-60
-40
-20
0

Frequency (MHz)

28dB
51dB

Active (QHX) Uncancelled

Interference Leakage (dBm)

0
2
4
6
8
10

Frequency Separation (MHz)

Sideband leakage is a showstopper for Picasso
Picasso: RF Front End Slicing

A) Active (QHX) Balun Cancellation [Mobicom’11]
- Balun (Used as signal inverter)
- QHX220
- RSSI
- Dynamic Cancellation Loop

B) Single Antenna Passive Cancellation (Picasso)
- Power Splitter
- Circulator
- Passive Attenuation and Delay
- Balun (Used as subtractor)

1) No Sideband Interference Leakage
2) Eliminates Need for Separate Antennas
3) Requires No Dynamic Adaptation
A. Single Antenna Full Duplex

1) Enables TX/RX chains to share antenna
2) Static and predictable response

Limited Isolation (≈15dB) between TX/RX (Ports 1 and 3)
B. Leakage-Free Passive Cancellation

[Diagram showing the components and flow of signals in a leakage-free passive cancellation system, including a Power Splitter, Passive Cancellation, Passive Attenuation and Delay, and RSSI Feedback.]
B. Leakage-Free Passive Cancellation

Diagram showing the components and flow of signals in a leakage-free passive cancellation system. The diagram includes a circulator, power splitter, passive cancellation, passive attenuation and delay, balun (used as subtractor), and RSSI feedback. The diagram also illustrates the reference signal and interference signal paths.

Legend:
- TX Signal
- RX Signal
- Reference Signal
- Interference Signal

Axes:
- X
- Y
B. Leakage-Free Passive Cancellation

- TX Signal
- RX Signal
- Power Splitter
- Passive Cancellation
- Passive Attenuation and Delay
- Balun (Used as subtractor)
- RSSI Feedback

- Reference Signal
- Interference Signal
- Residual
B. Leakage-Free Passive Cancellation

[Diagram showing passive cancellation process with components like TX and RX signals, Power Splitter, Passive Attenuation and Delay, Balun (used as subtractor), and RSSI Feedback.]
B. Leakage-Free Passive Cancellation

Circulator → Power Splitter → Balun (Used as subtractor) → Passive Attenuation and Delay → RSSI Feedback

TX Signal → Reference Signal
RX Signal → Interference Signal

Residual ← Y → X
Z
B. Leakage-Free Passive Cancellation

Diagram showing the process of passive cancellation with TX and RX signals, power splitter, passive attenuation and delay, and RSSI feedback. The diagram also includes a vector representation of reference signal, interference signal, and residual signal.
B. Leakage-Free Passive Cancellation

Passive and programmable delay lines are not readily available, limiting our ability to deal with phase mismatch.
B. Leakage-Free Passive Cancellation
B. Leakage-Free Passive Cancellation

Picasso’s passive and leakage-free cancellation can still be adjusted for changing environmental factors.
1) Single antenna full duplex
2) Fixed delay and passive resistive attenuation
3) Negligible energy to power circuit
2. Filter Engine - Programmable Processing

Self Interference Cancellation

LNA/LO

DAC

ADC

Filter Engine

TX

Rx

Digital Baseband TX Streams from Protocols

PHY/MAC

PHY/MAC

PHY/MAC

Digital Baseband RX Streams to Protocols

-\( F_s/2 \)

-\( F_s/2 \)

2.4 GHz

2.5 GHz

0

0

+\( F_s/2 \)

+\( F_s/2 \)
2. Filter Engine - Programmable Processing

Filter Engine performs 1) Digital Filtering, 2) Mapping from Fragments, 3) Resampling
Putting it All Together

- Self Interference Cancellation prevents receiver saturation, enables signal conversion to digital.

- Can use programmable baseband digital processing to process/shape signal.
Prototype Specs

Self Interference Cancellation

Balun

Passive Attenuation + Delay

Circulator

Single Antenna

Spectrum Slicing (NI PXI-7695)

ADC/DAC (NI 5781)

Picasso cancellation realized in a custom RF board built with off the shelf components
Benchmark Evaluation Setup

Picasso Radio

1MHz

Tx/Rx₁  Tx/Rx₂  Tx/Rx₃  Tx/Rx₄
How does a Picasso radio using 4 different slices compare to 4 independent radios using each fragment independently?
Throughput Performance Relative To Independent Links

Picasso achieves the same throughput over multiple links as multiple independent radios
Throughput Performance Relative To Independent Links

For guardband separations as small as 1 MHz, Picasso throughput does not suffer
Coexistence in Dense Environments with Picasso

Comparisons
- Multiple Radios (Optimal Scheme)
- SWIFT (OFDM PHY + 802.11e CSMA)
Coexistence in Dense Environments with Picasso

Picasso eliminates contention latency, allowing it to provide QoS guarantees whereas SWIFT cannot.
Future Work and Applications

Piecemeal spectrum allocation is causing licensed spectrum fragmentation
Future Work and Applications

Piecemeal spectrum allocation and licensing of single-licensed spectrum fragments
Future Work and Applications

Piecemeal spectrum allocation is causing licensed spectrum fragmentation

Usable bands are baked into hardware - phones do not work across carriers or geographies
Conclusions

- Picasso *decouples* the usage of individual spectrum fragments

- Substrate which enables wireless radios to systematically exploit fragmented spectrum

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APPENDIX
B. Leakage-Free Passive Cancellation

Picasso’s passive and leakage-free cancellation can still be adjusted for changing environmental factors.
Throughput Performance Relative To Independent Links

14dB ADC dynamic range handles large gaps between signal powers in concurrently active slices