Flexible Architectures for Concurrent Reception of Multiple RF Carriers and Compressed-Sampling Signal Detection in Frequency and Direction-of-Arrival

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***Abstract*— The modulated-clock downconversion mixer (MC-DM) and the antenna-weight-modulated phased-array (AWM-PA) are explored as key enablers of ambient-aware, opportunistic receivers in emerging 5G deployments. The benefits of the MC-DM is demonstrated first with an out-of-channel interferer reflecting, inter-band carrier aggregation receiver architecture where the RF carrier combination is selected simply by programming the frequency of the CW waveform used to modulate the mixer clock. Second, a wideband spectrum scanner architecture utilizing pseudo-random modulation of the downconversion mixer clock and Compressed-Sampling (CS) DSP is explored where a few large interferers are detected in ns time. The benefits of the AWM-PA is demonstrated with a phased-array architecture utilizing pseudo-random modulation of the antenna weights and CS DSP where a few large DoAs are detected in us time.**

***Index Terms*—Cognitive radio, dynamic medium access, carrier aggregation, phased-array receiver, compressed sampling, spectrum scanning, direction-of-arrival finding.**

I. Introduction

Advances in cognitive radio (CR) based dynamic shared medium access (DSMA) [1] systems will force us to rethink the radio transceiver. Future CR-DSMA receivers will rapidly gain awareness of their fast changing RF environment and opportunistically access a shared pool of frequency and angle resources. An ambient-aware receiver suitable for CR-DSMA depicted in Fig. 1 will include carrier-aggregation (CA) receivers, phased-antenna-array (PAA) receivers capable of beam and null steering, a sensing toolbox and a dynamic link management (DLM) engine. The sensing toolbox will include hardware and software elements that reuse the CA and PAA receiver hardware to realize rapid spectrum scanners and DoA finders. The DLM engine will use information from the sensing toolbox to reconfigure the signal receivers and opportunistically access the shared frequency and angle resources.

II. Motivation and Requirements

LTE Licensed-Assisted Access (LAA) [2] is considered as a usecase of DSMA where LTE terminals opportunistically form links in licensed and unlicensed bands. Fig. 2 illustrates a time snapshot of the dynamic

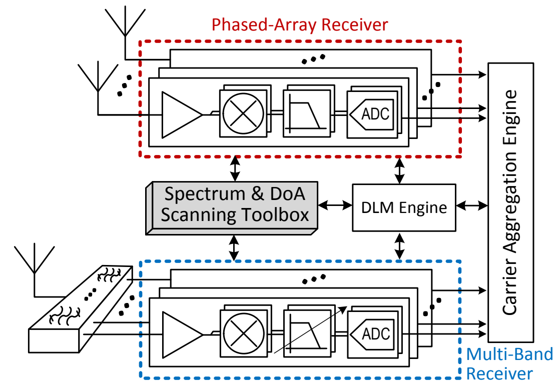

Fig. 1: *A conceptual illustration of an ambient-aware receiver frontend suitable for opportunistic DSMA.*

RF environment that the LTE-LAA terminal may have to operate in. The LTE-LAA terminal will first rapidly detect the location of strong signal components within its operating bands to construct a resource exclusion list and second perform energy-detection based clear channel assessment (CCA) on a set of candidate resources outside of the exclusion list to check for peer devices. The LTE frame duration is assumed to be 300us with 50us allocated for control signaling [3]. This extremely short-duration frame is designed to enable fast link-direction switching in order to achieve the 1ms round-trip latency goal of 5G. An additional 25us is allocated for the two-step sensing procedure proposed above for LTE-LAA.

The spectral mask around large signal components in Fig. 2 (or the LTE-LAA receiver's blocker 1dB compression point [4], [5]) is considered when constructing a channel exclusion list. Several adjacent resources surrounding each of the large signal components located at carrier frequencies $f_1, f_2 \cdots f_{K_0}$ and angles of arrival $\theta_1, \theta_2, \cdots \theta_{K_0}$ as illustrated in Fig. 2 are unusable for reception as the leakage into these resources may exceed the required CCA energy detection threshold [2]. The LTE terminal is thus left with a few usable candidate resources in the shared resource pool as depicted in Fig. 2. The LTE-LAA terminal will now randomly select a resource from

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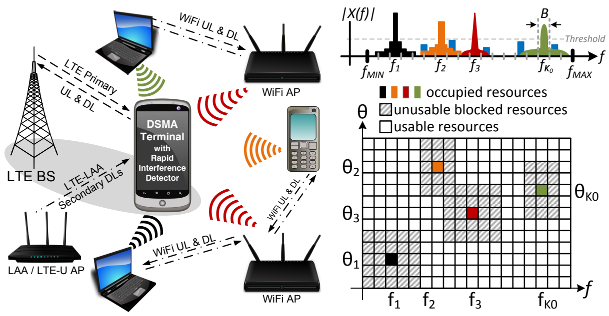

Fig. 2: *DSMA deployment scenario and a time snapshot of frequency (f) and angle (θ) resources available to the DSMA terminal in a cluttered multi-user RF environment.*

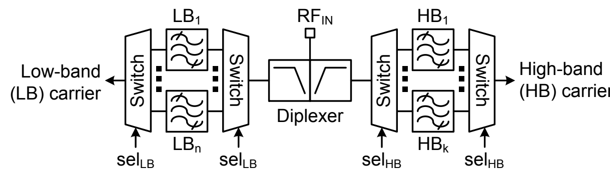

Fig. 3: *A SAW filter based antenna interface for aggregating two RF carriers from e.g. a set of high frequency ($HB_1 \cdots HB_k$) and a low frequency ($LB_1 \cdots LB_n$) bands.*

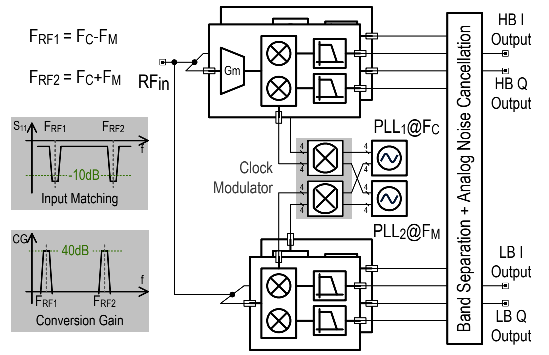

Fig. 4: *SAW-less flexible tuned matching and reception concurrently on two RF carriers using CW-modulated mixer clocks in the frequency-translational noise-cancelling receiver.*

TABLE I: *Features enabled by the MC-DM and the AWM-PA in direct-downconversion and beamforming receivers.*

	Modulation Disabled	Modulation Enabled — Modulation Waveform Type: CW	Modulation Enabled — Modulation Waveform Type: Pseudo-Random
MC-DM	Noise cancelling reception on a single RF carrier	Matching & reception concurrently on two RF carriers with noise cancellation	CS rapid wideband spectrum scanning
AWM-PA	Delay-and-sum beamforming reception	N/A	CS rapid direction of arrival finding

the candidate list and perform CCA for a duration of 9us [2]. If the chosen resource contains energy above the CCA threshold, the LTE-LAA terminal will randomly select a different resource on the candidate list. Assuming that at least 2 CCA trials are needed to find a suitable channel in the candidate list, we are left with 3.5us for the rapid detection of a few large signal components in frequency and DoA. In summary, future DSMA receivers will require compact reconfigurable architectures that can perform (i) flexible inter-band carrier aggregation (ii) rapid wideband spectrum scanning and (iii) rapid DoA finding.

III. Architectures Enabled by the MC-DM and the AWM-PA

Architectural features enabled by the MC-DM and the AWM-PA in direct-conversion noise-cancelling and delay-and-sum beamforming receivers are summarized in Table I as a function of the waveform type used to modulate the downconversion mixer clock and the antenna weights.

A. Flexible Tuned Matching and Reception Concurrently on Two RF Carriers

A SAW-filter based antenna interface for aggregating two RF carriers from e.g. a set of high-frequency bands ($HB_1 \cdots HB_k$) and a set of low-frequency bands ($LB_1 \cdots LB_n$) is illustrated in Fig. 3. A diplexer is used to separate the input signal (RF_{in}) into its high and low frequency components. A bank of bandpass SAW filters and switches are then used to select the two desired RF carriers from the low and hing frequency band clusters. The complexity of this antenna interface quickly becomes infeasible as the number of bands in the low and high frequency clusters increases.

In contrast, the modulated-mixer-clock receiver (MCM-RX) [6] shown in Fig. 4 employs a SAW-less antenna interface consisting of a mixer-first arrangement utilizing MC-DMs to deliver tuned matching simultaneously on two RF carriers f_{RF1} and f_{RF2}. The two RF carriers are selected simply by setting the frequency f_M of a CW waveform used to modulate the clocks used to drive the downconversion mixers. While the receiver architecture in [7] is capable of tuned matching concurrently on two RF carriers, the MCM-RX delivers better noise figure and out-of-band blocker immunity. An additional arrangement (Fig. 4) consisting of low-noise transconductance amplifiers (LNTAs) and MC-DMs in combination with the mixer-first arrangement and band separation DSP is used to concurrently enable two high-Q frequency responses at f_{RF1} and f_{RF2} in the MCM-RX. Noise cancellation [4] DSP is used to cancel the noise from the mixer-first arrangement leaked into the LNTA arrangement thereby enabling high-sensitivity reception concurrently on two separate RF carriers.

B. Compressive-Sampling Rapid Wideband Detection of Signals in Frequency

The MMC-RX [6] is a reconfigurable architecture suitable for inter-band carrier aggregation and compressive-sampling (CS) rapid wideband spectrum scanning. The spectral location of a few large signal components in a wide frequency span may be detected in less than 1us using MC-DMs driven by pseudo-random bit sequence (PRBS) modulated clocks and CS DSP [6], [8]. In CS detection mode, the MC-DMs in the mixer-first section of the MCM-RX are driven with a PRS modulated multi-tone clock, thereby upconverting the baseband TIA response to multiple adjacent RF frequencies terminating the antenna with a wideband load and thus enabling a wide frequency response. Multiple unique superpositions of all channels from the entire wide span are created using unique PRBSs and CS DSP is used to find the spectral location of a few large signal components.

C. Compressive-Sampling Rapid Direction-of-Arrival Finding

The Direct Space-to-Information Converter (DSIC) [5] shown in Fig. 5 is a unified architecture for delay-and-sum reception and CS DoA finding. The DSIC employs an AWM-PA to compactly introduce rapid CS DoA finding to an analog beamforming receiver. In CS detection mode, pseudo-random modulation of the antenna phase shifts implemented at baseband is enabled creating a wide antenna pattern as illustrated in Fig. 5 thereby simultaneously collecting energy from all directions in the span. Multiple unique superpositions of all directions from the entire span are created sequentially in time and CS DSP is used to find the DoAs of a few large signal components in 1us. In reception mode antenna weight modulation is disabled and delay-and-sum reception on a single DoA is enabled. While the architecture in [9] does enable rapid CS DoA finding, it uses dedicated banks of hardware for each CS measurement and thus the hardware complexity of this architecture becomes infeasible as the number of required DoAs increases.

IV. Discussion and Conclusions

The benefits of the MC-DM and the AWM-PA have been demonstrated with two architectures - (i) the MCM-RX and (ii) the DSIC. The MCM-RX delivers tuned matching and reception concurrently on 2 RF carriers. While the architecture in [7] does deliver tuned matching and reception concurrently on 2 RF carriers, the MCM-RX delivers better noise figure and almost an order of magnitude improvement in out-of-band blocker immunity. The DSIC compactly adds CS DoA finding to a delay-and-sum analog beamforming receiver. In contrast, the architecture in [9] for CS DoA finding employs dedicated hardware banks for each CS measurements. This makes the hardware complexity of this architecture infeasible as the number of DoAs increases. The functional flexibility combined with fast reconfigurability of the MCM-RX and the DSIC has the potential to enable future cognitive radio terminals that rapidly gain awareness of their fast changing ambient environment and opportunistically gain access to a shared pool of frequency and angle resources while meeting the cost, size and power targets in mass-market applications.

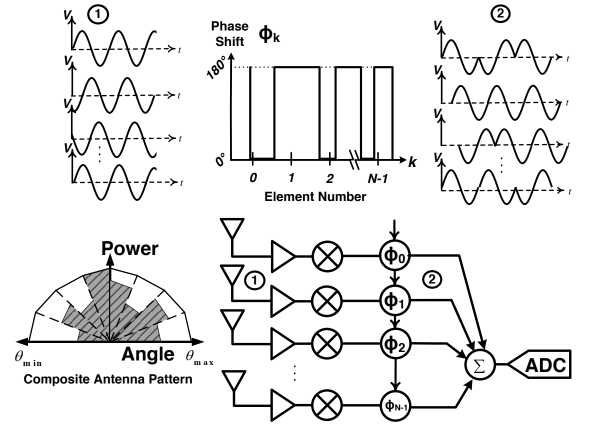

Fig. 5: *Rapid detection of the DoA of a few large signal components using pseudo-random modulation of antenna phase shifts in a delay-and-sum analog beamforming receiver.*

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