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Spectrally efficient emission mask shaping for OFDM cognitive radios

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ABSTRACT

Orthogonal Frequency Division Multiplexing has been widely adopted in recent years due to its inherent spectral efficiency and robustness to impulsive noise and fading. For cognitive radio applications in particular, it can enable flexible and agile spectrum allocation, yet suffers from spectral leakage in the form of large side lobes, leading to inter-channel interference unless mitigated carefully. Hence, recent OFDM-based standards such as IEEE 802.11p for vehicular communication and IEEE 802.11af for TV whitespace reuse impose strict spectrum emission mask limits to combat adjacent channel interference. Stricter masks allow channels to operate closer together, improving spectral efficiency at the cost of implementation difficulty. Meeting these strict limits is a significant challenge for implementing both 802.11p and 802.11af, yet remains an important requirement for enabling cost-effective systems. This paper proposes a novel method that embeds baseband filtering within a cognitive radio architecture to meet the specification for the most stringent 802.11p and 802.11af masks, while allowing up to ten additional active 802.11af sub-carriers to occupy a single basic channel without violating SEM specifications. The proposed method, performed at baseband, relaxes otherwise strict RF filter requirements, allowing the RF subsystem to be implemented using much less stringent 802.11a designs, resulting in cost reductions.

1. Introduction and related work

Orthogonal Frequency Division Multiplexing (OFDM) has been adopted for many wireless standards as well as being an important enabling technology for cognitive radios. However, one of its main disadvantages is spectral leakage due to the summation of sinusoidal sub-carriers which are then widowed by a rectangular function. This has led to some recent OFDM-based standards demanding strict limitations on leakage into adjacent channels, in order to reduce inter-channel interference (ICI). In particular, this paper considers two such standards that impose strict limits on ICI; IEEE 802.11p, for Dedicated Short-Range Communications (DSRC) and IEEE 802.11af for cognitive radio access within television whitespace (TVWS) spectrum. This paper presents, discusses, implements, and evaluates a novel architecture capable of meeting the imposed adjacent channel interference limits defined by both OFDM standards.

1.1. 802.11p physical layer

In 2010, the IEEE defined the IEEE 802.11p standard for PHY and MAC layers [1], aimed at providing dedicated wireless links for new vehicular safety applications through vehicle-to-vehicle (V2V) and Road to Vehicle (RTV) communications. The IEEE 802.11p PHY was largely inherited from the well-established IEEE 802.11a OFDM PHY, with several modifications aimed at improving performance in vehicular environments. Basing the PHY on 802.11a reduces development efforts for 802.11p hardware and software, by enabling design re-use. It also allows backwards compatibility with 802.11a [2,3]. In essence, three main changes were made in moving from 802.11a to 802.11p:

1. A 10 MHz channel width instead of the 20 MHz in 802.11a. This extends the guard interval to address the effects of Doppler spread and inter-symbol interference inherent to vehicular communications.
2. Improved adjacent channel rejection performance in the receiver to reduce the effect of cross channel interference, again especially important in vehicular communication channels [4].

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3. Four spectral emission masks (SEMs) specified and mandated in FCC CFR47 Sections 90.377 and 95.1509. These class A to D specifications are all more stringent than those for current 802.11 radios.

In addition, 802.11p operates in the 5.9 GHz DSRC region which is divided into seven 10 MHz bands. This channelisation allows the MAC upper layer to perform multi-channel operations [5] and allows safety and other applications to occupy separate channels in order to manage and reduce interference. The four strict SEMs aim to reduce the effect of ICI between these channels although Wu et al. have shown that transmitters on adjacent service channels still cause ICI in the safety channel, even when they satisfy the class C requirement [6]. Shaping the 802.11p spectrum in order to reduce leakage and thus ICI is therefore important.

Thanks to the similarities between the two PHYs, some researchers have focused on adapting 802.11a PHY devices for 802.11p [7,8,2]. The transformation is typically accomplished in four parts, namely, reducing channel bandwidth, channel estimation, satisfying transmission power requirements, and ensuring effective channel access performance. Due to a dearth of affordable 802.11p prototype hardware, existing wireless testbeds for 802.11p tend to use modified 802.11a implementations [7]. For example, Almeda and Matos present a front-end using 802.11a hardware that is targeted to comply with 802.11p [9]. However, despite strict constraints, it does not meet the SEM requirements. Fuxjäger et al. similarly presented a transmitter implementation using the GNU Radio software-defined radio platform [10]. Despite being functional, the signal spectrum contained two peaks at image frequencies, which the output filter was unable to remove, and hence did not satisfy even the class A (most relaxed) SEM. Meanwhile, an early prototype transceiver based on a modified Atheros chipset [10], was able to fulfil class A requirements, but not classes C or D. It is clear that the stringent SEMs significantly increase the difficulty, and hence cost, of implementing new silicon or hardware for 802.11p. In fact, there has been much debate regarding whether and when chip makers will be able to meet such challenging requirements [4]. To the best of the authors' knowledge, no implementations or testbeds for 802.11p have been published that are able to meet the class D specification, prior to our own very recently published technique in [11].

1.2. 802.11af physical layer

In 2009, the FCC issued regulatory rulings for the reuse of television whitespace (TVWS) spectrum. In response, the 802.11 Working Group (WG) issued standard IEEE 802.11af to enable Wi-Fi in TVWS [12]. Continuing the theme of reuse, the standard defines amendments to existing high throughput 802.11ac PHY and MAC specifications to meet the requirements for channel access and coexistence in the TVWS region. Again, one of the main challenges is the stringent SEM requirement, which has been mandated by the FCC in the US and Ofcom in the UK. At present, a large gap exists between the spectral emissions of a scaled 802.11ac PHY and the mandated SEM for TVWS [13]. For instance, a (scaled) 802.11 implementation achieves an attenuation of 20 dB at the edge of the channel, whereas the requirement for portable TV band devices (TVBD) is 55 dB [14]. A working implementation was demonstrated by Lan et al. who presented the first prototype system of Wi-Fi in TVWS based on the 802.11af draft specification [14]. Their implementation achieved an attenuation of 35 dB at the edge of the channel, which is still far from meeting the required SEM.

1.3. Implementation

Modern OFDM implementations tend to favour subsuming as much processing as possible within the baseband digital components, in order to simplify the front-end RF hardware. Although many alternative transmitter designs exist, direct up-conversion (DUC) architectures are commonly selected due to inherent implementation, cost and performance advantages [15]. Within the transmitter, orthogonal intermediate frequency (IF) signals are generated directly by digital baseband hardware, high-pass filtered, and then quadrature up-converted to RF for transmission. This contrasts with more traditional digital radio implementations in which the digital hardware generates baseband signals which are up-converted to IF in one or more analogue steps before conversion to RF. Those systems would perform channel filtering predominantly with analogue filters, which require discrete precision components, and which tend to be inflexible in terms of carrier frequency and other characteristics. For cognitive radio (CR) systems, where frequency agility is a requirement, and in SDR (software defined radio), both up-conversion to IF as well as channelisation filtering are performed in the digital domain [16,17]. Typically, this enables a relaxation of stringent IF and RF filtering requirements, which in turn allows a reduction in system cost, though requiring more complex signal processing. A further advantage of baseband filtering is agility and flexibility. In a CR context in particular, both channel and time agility are required, and this can be best achieved in the digital domain.

Within the baseband, OFDM symbols are constructed in the frequency domain and then transformed to a complex time domain representation through the IFFT. A critically sampled construction process requires a sample rate of double the signal bandwidth. This signal is up-converted to IF using an interpolation process, during which images of the original OFDM frequency response are created at integer multiples of the original sampling rate. Image rejection filtering must then be performed on this signal prior to output by the digital-to-analogue converters (DACs) and subsequent transmission, since the images lie out-of-band (OOB) and hence are a cause of ICI.

However any such filtering induces time-domain smearing of the transmitted signals [18,19] which adds to the similar effects caused by the channel impulse response (CIR) between transmitter and receiver, all of which potentially induce inter-symbol interference (ISI).

OFDM systems combat ISI by dividing information finely in the frequency domain across sub-channels to implement narrow (in frequency) but long (in time) transmitted symbols, and then providing a guard interval between successive symbol blocks. The guard interval is determined by the duration of the expected channel and filter impulse responses that are traversed by each symbol on the path from transmitter baseband to receiver baseband. The guard interval typically contains a cyclic prefix (CP) which is inserted to combat another cause of ISI: received frequency components ringing during the CIR due to the abrupt onset of modulation at the beginning of each symbol. The nearly rectangular OFDM symbols in the time domain naturally have a frequency domain response consisting of overlapping sinc shapes, complete with large side lobes that lie outside the main frequency channel. These are another source of OOB interference which contributes to ICI. As noted previously, both 802.11p and 802.11af (in common with most OFDM-based standards) specify an SEM which requires that ICI is controlled.

In general there are two methods of achieving a given SEM. The first is to perform sharp filtering within the analogue RF transmission chain, while the second is to use digital baseband filtering techniques (which we have noted are generally considered to be advantageous in terms of flexibility, cost, design effort, size and component count). RF filtering methods were adopted in early SDR OFDM implementation like [17], and involve expensive hardware components such as oven-controlled crystal oscillators and precision passives, as well as adherence to tight design and