OFDM SUB-CARRIER ALLOCATION ALGORITHM FOR A MULTIPLE USER DATA ENHANCED RADIO SERVER (MUDERS) USING A GENERAL PURPOSE PROCESSOR PLATFORM

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1. ABSTRACT

This paper presents a novel spectrum-allocation technique designed for a high data-rate and spectrally-efficient multiple-user wireless system. The core of this system is a reconfigurable radio, implemented on a General-Purpose Processor (GPP) platform. A type of Dynamic Orthogonal Frequency Division Multiplexing Multiple Access (DOFDMA) is used to transmit a multiplex of several information sources. A novel means of sub-carrier allocation is utilised allowing the spectrum allocation for each service to be varied according to the spectrum-usage at the time of the request and priority of the particular service. In addition a novel technique that enables frame synchronisation, carrier-frequency offset estimation and a means of notifying the remote receiver(s) of the sub-carrier allocation using a single OFDM symbol will be presented. A prototype model for the Multiple User Data Enhanced Radio Server (MUDERS) modulator will be presented, focusing on a means of conveying the spectrum allocation information to a remote receiver(s).

2. INTRODUCTION

The Multiple User Data Enhanced Radio Server (MUDERS) system is a transceiver system designed for communities that may, for example, have an established Ethernet system but require access to a wireless bridge between two networks. This system is designed for all-IP networks as envisioned for Fourth Generation (4G) wireless communication networks and beyond, as a means of traversing short distances between two IP-based networks or devices.

In an office building implementation example, the office staff may communicate normally through the fixed Ethernet network for inter-office messages. A new administration or faculty building, which is located across a busy street, requires full access to the fixed network in the parent building's Ethernet network. A fixed network connection to this sub-office may be difficult to implement, expensive, and may also require physical modification to the installed networks in both buildings. A wireless network bridge using a Commercial Off The Shelf (COTS) GPP OFDM reconfigurable transceiver system offers a much less expensive, easily installed, and rapid solution to this problem than dedicated DSP hardware alternatives.

The MUDERS system, illustrated in Figure 1, is an end-to-end IP system acting as a wireless bridging point employing DOFDMA as the transmission technology and based on a GPP reconfigurable radio platform using an implementation of a reconfigurable radio framework called Implementing Radio In Software (IRIS) developed by the Networks and Telecommunications Research Group (NTRG). OFDM is an ideal choice of modulation/access scheme due to its inherent frequency-diversity and high data-rate capabilities in addition to its ease of implementation in the software domain. Spectrum-allocation is a valuable technique for dealing with busy and unlicenced frequency bands such as the 2.45 GHz Industrial, Scientific and Medical (ISM) band. The focus of this paper, therefore, is to present a novel low-complexity spectrum-allocation scheme that may also operate as a frame synchronisation and carrier frequency offset estimation technique at the receiver, which may be achieved using the reconfigurable radio platform.

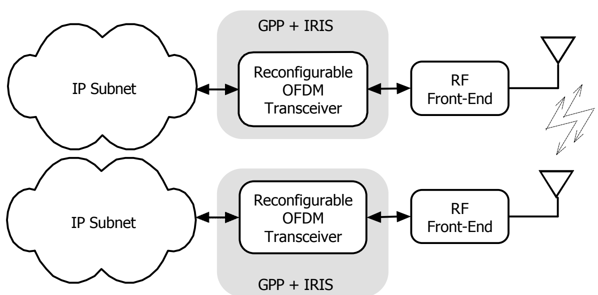

Figure 1: Overview of the MUDERS system

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3. BACKGROUND

As the capabilities and signal-processing power of software radio/reconfigurable radio technology improves rapidly, spectrum allocation is now a feasible option for improving communications over increasingly crowed frequency bands. Recent studies of how to improve the capacity of multi-user transceiver systems have favoured the characteristics of OFDM and a means of dividing a spectrum segment between users based on the priority of their requirements and the gain of each channel using a 'water-filling' concept [1][2]. Schmidl and Cox examine the use of a training sequence of two OFDM symbols to correct the carrier frequency offset and estimate the start of frame position. This technique is called Maximum-Normalized Correlation Timing and Carrier Frequency Offset (CFO) estimation [3]. When each training symbol, which has two identical halves has passed through the channel, the carrier frequency offset may be calculated from the phase difference between the two symbol halves. The research work presented in this paper is also based on subsequent enhancements to Schmidl and Cox's frame synchronisation technique adapted for GPP-based reconfigurable radio [4]. The IRIS reconfigurable radio development and implementation platform developed by Mackenzie and the NTRG is based on a suite of highly reconfigurable modular radio components implemented in software as dynamically-linked libraries (DLLs). IRIS was designed specifically for rapid and efficient reconfigurable radio deployment using a XML configuration for initial radio description [5].

4. DYNAMIC OFDM MULTIPLE ACCCESS

The core of DOFDMA is Orthogonal Frequency Division Multiplexing (OFDM), which is a multi-carrier modulation/channel access scheme that uses several orthogonal carrier frequencies (or sub-carriers) to transmit information. Consider an OFDM transceiver system with N_{SC} useful sub-carriers used for transmission, using a FFT of length N_{FFT} . An OFDM symbol is a multiplex of orthogonal sub-carriers, created in the frequency-domain initially and then converted to a time-domain waveform using the Inverse Fast Fourier Transform (IFFT). A data symbol is a point on a constellation diagram of a chosen modulation scheme that represents a modulated grouping of one or binary values depending on the specific modulation scheme. A modulation scheme such as 16-QAM may represent a grouping of four binary values as one data symbol. Each sub-carrier value comprised one complex-valued data symbol. The OFDM signal is generated at base-band by performing an Inverse Fast Fourier Transform (IFFT) on the complex-valued sub-symbols, $X(k)$ as follows:

$$x(n) = \frac{1}{N_{FFT}} \sum_{k=0}^{N_{FFT}-1} X(k) \exp\left\{ j2p \frac{nk}{N_{FFT}} \right\} \qquad (1)$$

A guard interval is formed by cyclically extending the last N_{GI} samples of the OFDM symbol, where N_{GI} denotes of the length of the guard interval. If this guard interval is longer than the coherence bandwidth of the channel, the possibility of Inter-Symbol Interference (ISI) may be minimised. Prior to demodulation of an intercepted digitised OFDM baseband waveform, this guard interval is removed and the waveform is de-multiplexed by performing a FFT on the truncated received OFDM symbol, $y(n)$. The value $Y(k)$, which is the value of the *k*-th sub-carrier, after the FFT process (i.e. the data symbol associated with this sub-carrier may be expressed as

$$Y(k) = \sum_{n=0}^{N_{FFT}-1} y(n) \exp\left\{ -j2p \frac{nk}{N_{FFT}} \right\} \qquad (2)$$

A binary data sequence is converted to *N* parallel subsets of the sequence, where *N* is the number of sub-carriers available for transmission. For this particular DOFDMA scenario, multiple unique input data sequences are converted into N_{ss} data sequence subsets, where $N_{ss} = N_{SC} / N_{SRV}$, N_{SC} denotes the number of available sub-carriers for transmission and N_{SRV} denotes the number of unique information sources (users) that require access to the wireless medium. Each sub-carrier may then transmit the information contained in each sub-set and all of the sub-carriers may be transmitted in unison resulting in significantly greater data rates than single-carrier systems. An OFDM frame is a sequence of OFDM symbols, where each OFDM symbol is the time-domain representation of the multiplexed sub-carriers following the Inverse Fast Fourier Transform (IFFT) stage in the transmitter. The OFDM frame therefore consists of a sequence of *N* OFDM symbols preceded by a frame guard. This frame guard is longer than the guard-interval between two successive OFDM symbols and may be used for synchronising the receiver to the transmitter. One of the main issues with multi-carrier modulation methods is that multi-path, flat and/or Doppler fading, noise and/or interference may result in the unrecoverable loss of the information associated with one or more sub-carriers. Block-interleaving techniques reduce this risk but this paper proposes a dynamic spectrum allocation scheme that offers to reduce the possibility of information loss even further using a carrier-avoidance spectrum allocation technique.

5. RECONFIGURABLE RADIO

Reconfigurable radio is a term that describes a software radio where the application, structure and parameters of the software radio may be modified or replaced even while the radio is in operation. A transmitted signal is subject to

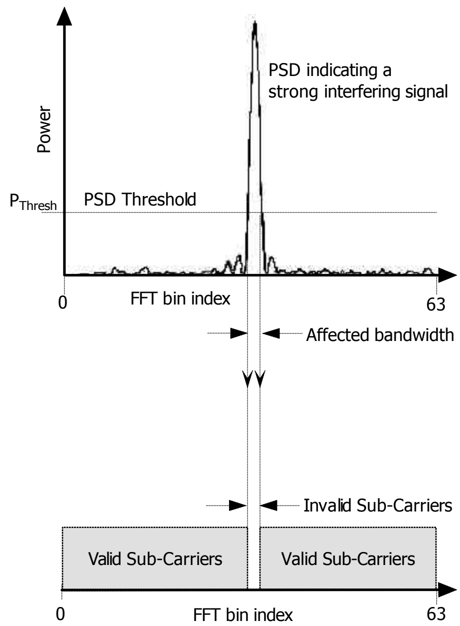

Figure 2: Selecting sub-carriers using PSD threshold selection

the effects of the wireless communications channel. The signal may be affected by noise, interference from natural and man-made sources and fading effects. Noise sources include Additive White Gaussian Noise (AWGN), coloured, impulse and thermal noise due to the receiver. Fading effects include flat fading resulting from a reflective body usually between the transmission source and receiver, Doppler fading due to a mobile transmitter and/or receiver and multi-path fading. A reconfigurable radio may automatically adapt to the continuously changing wireless channel environment in order to maximise the channel capacity usage. In this paper, the time-variant characteristics of the wireless communication channel are used as part of the transceiver decision process. Specifically, this means that the sub-carriers that may be used for information transmission are chosen based on the instantaneous signal power measured for each sub-carrier. The reconfigurable radio may decide not to choose a sub-carrier if this measured signal power is above a specified threshold level, indicating that this sub-carrier is experiencing interference, noise or is in use by another adjacent transmitter. The spectrum-allocation, symbol-mapping and OFDM pilot symbol generation stages reconfigure themselves each time a new OFDM frame is required to be transmitted. The receiver must then reconfigure the OFDM demodulation and symbol de-mapping stages based on information from the received OFDM pilot symbol. This type of reconfigurability is at the parameter-level, which is the lowest layer of reconfigurability possible for a reconfigurable radio. The target test-bed for this proposal is capable of dealing with dynamic structural and application-level reconfigurability in addition to the smaller granularity parameter-level modifications stated previously.

6. GENERAL PURPOSE PROCESSOR (GPP) PLATFORM

The proposed reconfigurable radio is based on a General-Purpose Processor (GPP) platform using an Intel x86 processor and a non real-time OS. This architecture enables the level of reconfiguration required for the flexible-architecture wireless device as on-the-fly radio structure and parameter changes are possible with less radio management complexity than a dedicated DSP approach. A GPP offers large amounts of programme memory to enable a complex implementation such as a reconfigurable transceiver to invoke large amounts of possibly processing power intensive signal-processing routines in addition to the fact that the performance of the radio follows the increasing processing speed trends. The Operating System (OS) used for the radio platform takes care of the memory management and thread scheduling tasks leaving the reconfigurable radio designer to concentrate on the creative radio functionality and structural concepts. A thorough description of the IRIS test-bed and implementation environment is beyond the scope of this paper however. The IRIS system is capable of implementing highly reconfigurable transceiver systems using a framework that enables individual signal-processing stages of a radio design to be dynamically modified, re-ordered, inserted or even removed using either automatically, using information from the receiver, and/or from the user.

7. SUB-CARRIER ALLOCATION SCHEME

Sub-carrier allocation is used in OFDM to decide which carrier-frequency (sub-carrier) will be used for each parallel subset of the original binary sequence representing the information source. In other words, each information service requiring access to the wireless medium is assigned a number of sub-carriers. The sub-carrier allocation scheme proposed in this paper enables data sequences of specific length from multiple information sources to be multiplexed onto one OFDM symbol. As the band of interest for this system is expected to experience significant interference from other sources of transmission activity due to the proliferation of 2.45 GHz ISM band devices, this proposal goes one step further to allocate only the sub-carriers which are not being used either intentionally or unintentionally by other transmission sources. The main reason for this is to maximise the possibility that a transmitted signal on a specific sub-

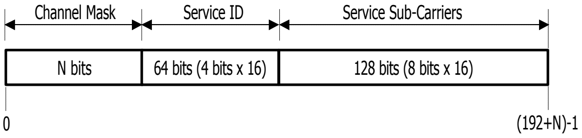

Figure 3: MUDERS pilot symbol structure

carrier will be conveyed to the destination receiver without being corrupted beyond recovery by other transmissions already using that particular sub-carrier. The specific sub-carriers used depend on the activity monitored on each carrier frequency. The method used to decide which sub-carriers are used for information transmission is to mask the sub-carrier indices that have been deemed unusable by creating a channel mask. Sub-carriers are deemed to be unusable if the power-spectral density associated with a particular sub-carrier in a received signal sequence exceeds the pre-determined power-spectral density threshold value. This threshold value is determined by experimental tests based on the normalised power-spectral density of sequences of received signals. The proposed spectrum-allocation scheme in this paper uses the averaged PSD of a number of the equalised received signal sample sequences, updated on a per OFDM-frame basis to decide which sub-carriers may be used for transmission. As this technique may be classed as a carrier-avoidance spectrum allocation scheme, it is important to note that the initial sub-carrier allocation must be achieved when there are ideally no transmissions from associated MUDERS destination transceiver(s). In order to achieve regular updates of the channel PSD, the MUDERS system relies on a 'listen and update PSD history' cycle which means that the local receiver measures the PSD of the wireless channel following OFDM frame transmission and updates the PSD. This PSD information is then used to update the sub-carrier allocation. An improvement in performance may be achieved by only updating those carriers which were not-previously allocated due to previous PSD values above the PSD threshold. As shown in Figure 2, sub-carriers with a PSD greater than a this threshold value, P_{Thresh}, are not used for transmission of a the subsequent OFDM frame as the high PSD may indicate that these sub-carriers are affected by either noise, interference or are in use by another transmission source. By analysing the PSD of all of the possible sub-carriers before an OFDM frame is transmitted, a sub-set of sub-carriers, where the PSD associated with each sub-carrier is less than P_{Thresh} may be compiled. These valid sub-carriers may then be compiled to form a channel-mask. Emphasis is placed on maximising the number of sub-carriers that are may be employed to convey information. As a result of this, the sub-carriers which were not previously allocated due to a PSD value above a threshold value P_{Thresh}, are monitored and may be subsequently included in the active OFDM multiplex if $PSD(k) < P_{Thresh}$, where $PSD(k)$ is the power spectral density associated with the *k*-th sub-carrier. The channel mask operates as a means of defining which sub-carriers will be used for transmission prior to the OFDM generation process. The channel mask used in this spectrum-allocation scenario is not the same concept as an ITU spectrum mask which limits the spectral power following the creation of a multiplexed OFDM waveform prior to transmission. This mask consists of a binary array where each binary value corresponds to one sub-carrier index. The size of the spectrum mask is directly proportional to the total number of sub-carriers that may be used for transmission. One binary value is assigned to each of the sub-carriers, where the maximum number of sub-carriers is equal to $N_{FFT}/2$. Therefore, if a 128-bin FFT is used, the total number of sub-carriers that may be used for transmission is 64. If a sub-carrier is deemed unusable due to the previously mention PSD threshold criterion, a binary zero is stored in the channel mask array position corresponding to the index of the sub-carrier in question. A binary one in any of the channel mask array positions, as shown in Figure 3, denotes that the sub-carrier associated with this array position is available for data transmission. The set of available sub-carriers is then obtained by *AND*-ing the array of FFT-bin indices with the channel mask. Pilot symbols may be transmitted during each frame guard. These pilot symbols are special data symbols, or points on a constellation diagram corresponding to a specific modulation scheme, that may be used to correct frequency and timing offsets between the receiver and remote transmitter. Pilot symbols usually consist of data symbols corresponding to high-power constellation points in order to ensure that the receiver can detect them. As a result, the OFDM pilot symbol is generally of higher power than normal information-carrying (i.e. valid data-carrying) OFDM symbols. As the receiver usually has *a priori* knowledge of the specific pilot data symbols used, the receiver may then compare the received pilot data symbols to the expected phase and amplitude of the pilot symbols. Carrier frequency and timing offsets may manifest themselves as differences between the expected phase of the pilot data symbols and the actual phase of the received pilot symbol. As the duration of an OFDM symbol is very short, the communications channel may be considered to be stationary during this short interval. Frequency-domain equalisation may then be achieved by compensating for the differences in phase and amplitude between the expected pilot data symbols and the measured phase and amplitude values. Specially designed pilot data sequences may also be used as a means of estimating where the start of an OFDM frame occurs in an intercepted signal sequence. The sub-carrier allocation scheme proposed in this paper utilises the frame guard in order to inform the receiver of which sub-carriers have been chosen to convey information to the receiver also. This method has been chosen as it results in no extra synchronisation overhead in the valid data portion of the OFDM frame. The frame guard is used to transmit the sub-carrier allocation information as well as the pilot sequences.

Figure 3 illustrates the basic structure of an OFDM pilot symbol used for simulations. It is important to note that this structure may be modified at some future date as part of on-going development of the MUDERS system. The first N bits of this binary field, where N is the total number of sub-carriers available for transmission, correspond to the channel mask. The Service ID field contains the identifications of all the information services that are contained in the multiplex signal. The maximum number of services that may be accommodated in this case is $2^D - 1$, where D denotes the number of bits used to represent the service ID. Each valid service is represented by a non-zero 4-bit ID. The special case of a zero-value ID is reserved to indicate that no service exists and the receiver obtains the number of unique services that will be contained in the OFDM frame by counting all of the non-zero service IDs. Therefore for the 4-bit service ID case, a maximum of 15 services may be accommodated. The specific sub-carriers that relate to each service are contained in the Service Sub-Carriers binary field as also shown in Figure 3. A maximum of 15 unique services may be represented by an 8-bit value including the null ID which represents the *no-service* case. This value is the number of valid sub-carriers that each service uses. The number of services is limited by the FFT size used by the MUDERS system. For a 128-bin FFT, resulting in 64 possible sub-carriers, the total number of binary values required to represent one OFDM pilot structure is 256 bits. Using 16-QAM as the modulation scheme requires 64 carriers. If a less complex modulation scheme was employed, then there would be insufficient sub-carriers to enable the transmission of one pilot structure using just one pilot OFDM symbol. A modulation scheme with a

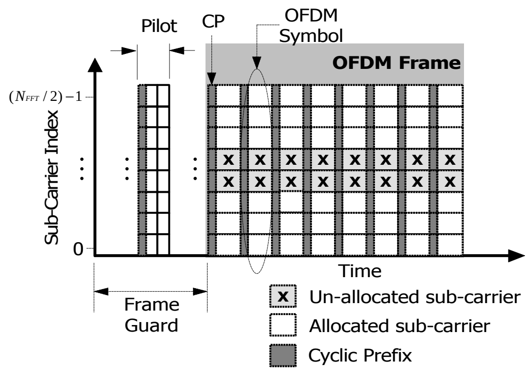

Figure 4: OFDM frame structure

higher bit-to-symbol ratio than 16-QAM may not robust enough for OFDM pilot transmission without channel coding. The sub-carrier allocation scheme proposed in this paper is based on the time-varying PSD of a sequence of received signals. The crucial part of this system is creating a means of conveying the resulting time-varying sub-carrier allocation information to the destination receiver(s) ideally without an alternate feedback channel. As the system outlined in this paper is a multi-user simultaneous transmission model, details of which sub-carrier belongs to which information service must also be furnished to the receiver(s). The transmission overheads must be minimised in order to maximise the amount of valid information that may be transferred to the destination over the wireless medium. The solution presented in this paper is to therefore take advantage of the frame guard, and a specific type frame synchronisation and carrier-offset correction technique and enhance its capabilities to enable the remote receiver to obtain the current sub-carrier allocation information. A reliable means of conveying this information to the destination receiver(s) must be devised.

If a new transceiver joins the MUDERS system while it is in operation, it must also be able to obtain the current sub-carrier allocation information. Therefore a means of allowing any MUDERS device to establish connectivity almost instantaneously means that the current sub-carrier allocation information must be conveyed to the new MUDERS wireless device using a transmission structure and method that is common to all MUDERS wireless devices. The sub-carrier allocation notification system proposed in this paper also functions as a frame synchronisation and carrier-frequency offset estimation scheme. OFDM frame synchronisation and CFO estimation may be achieved by transmitting one OFDM symbol consisting of two identical half-symbols at a specific point during the frame guard as shown in Figure 4. Each OFDM half-symbol consists of a specific number of pilot symbols. A pilot data symbol is a data symbol that does not actually represent valid information from the source(s) but may be used for receiver synchronisation and channel estimation. Pilot data symbols are chosen from the high-power signal constellation points of a digital modulation scheme such as 16-QAM. Frame synchronisation may be achieved by constructing OFDM symbols from the received signal sequence and correlating the two halves of each of the pilot OFDM symbols. A received pilot OFDM symbol will result in a significant increase in value of the correlator output as the two halves of this special OFDM pilot symbol are identical thus enabling the receiver to estimate the index of the start of the OFDM frame [3][4]. A carrier frequency offset between the receiver and the transmitter will manifest itself as a time-varying phase difference between the two halves of the OFDM pilot symbol. If the CFO is zero,

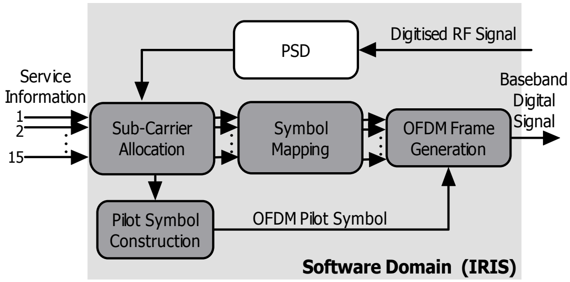

Figure 5: MUDERS reconfigurable modulator block diagram

then the phases of the first half of the OFDM pilot symbol will be exactly the same as the phases of the second half of the OFDM pilot symbol. Therefore a CFO estimate may be obtained by measuring the rate of change of the phases between the two half-symbols. The main enhancement to this frame synchronisation and CFO estimation scheme is that the pilot data symbols are not chosen arbitrarily but in fact are the modulated spectrum mask values denoting which sub-carriers will be used to transmit valid information from the multiple sources. This means that the N sub-carriers, where $N = (N_{FFT} / 2)$, represented by an array of N binary values, comprising the channel mask, are modulated using a modulation scheme such as 16-QAM. The chosen modulation scheme must be capable of representing the entire N binary value-set corresponding to the channel mask as well as ensuring that the pilot OFDM symbol is of higher power than the normal data-bearing OFDM symbols. This is required to maximise the possibility of the receiver detecting the pilot OFDM symbol in the first place. The sub-carrier allocation information as shown in Figure 3 may be obtained by demodulating the received pilot OFDM symbol to obtain the channel mask and service information.

8. MUDERS IMPLEMENTATIONAL MODEL

Figure 5 illustrates the basic block diagram of the MUDERS reconfigurable modulator implemented using IRIS on an Intel 2 GHz Pentium IV GPP with Windows™ XP (non real-time OS). The radio components which may be reconfigured on a per-frame basis are displayed as the darkest blocks in this figure. The motivation for reconfiguration is the PSD information of the baseband received OFDM waveform. An OFDM pilot symbol is constructed from the latest sub-carrier allocation information and inserted into the transmission sequence during the frame generation stage. The signal-processing blocks (or radio components) as shown in Figure 5 may be dynamically reconfigured through a set of software interfaces, which allows the IRIS system to access and modify the parameters of each of the inter-dependent radio components. The sub-carrier allocation algorithm may be reconfigured or replaced using this system; options include allocating valid sub-carriers to services based on the priority of the service, the length of the message queue for each service and incorporating adaptive PSD threshold levels based on the Bit Error Rate (BER) history and desired Quality of Service (QoS).

9. EVALUATION AND CONCLUSIONS

The sub-carrier allocation scheme presented in this paper is designed to avoid carrier frequencies that are being subjected to strong interfering transmissions which may result in the possible unrecoverable loss of information if that frequency was used for data transmission. The proposed technique also combines frame synchronisation and CFO estimation in conjunction with a means of informing the remote reconfigurable transceiver(s) of the current sub-carrier allocation information using a single OFDM symbol. Multiple services may therefore transmit information with a potentially lower BER and this technique may be developed further for forward-looking spectrum-management applications. Per-frame demodulation without *a priori* modulation scheme knowledge is envisaged by integrating modulation scheme recognition techniques into the MUDERS system to create a fully-adaptive reconfigurable transceiver.

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