MIMO-Interference Aware Scheduling Enabling the Allocation of Unbounded Co-channels in Unplanned Networks

Kranthi Manoj. Nagothu, Brian Kelley Senior Member IEEE, Mo Jamshidi Fellow IEEE,
Electrical and Computer Engineering, The University of Texas at San Antonio, TX, USA
Kranthimanoj@gmail.com, {brian.kelley, mo.jamshidi}@utsa.edu

Abstract— **We present novel opportunistic interference aware scheduling (IAS) for dynamic channel allocation reuse to dynamically allocate new channels in unplanned networks. We introduce high levels of co-channel interferers with coordinated spatial signatures. We view this as likely system scenario for cognitive radio (CR) networks based upon IEEE 802.22 and moreover support smart grid, information networks. The proposed algorithm cooperatively allocates MIMO-channels to users based on spatial separability criterion that we introduce. We derive the MIMO beamforming coefficients that optimally reduce spatial interference. Finally, simulation results indicating sizeable increases in the multiuser capacity are possible to support smart grid information networks.**

Keywords- cognitive radio, interference-scheduling, IEEE 802.22, unplanned networks

I. INTRODUCTION

A communication infrastructure is considered as an essential enabling component of the emerging smart grid. The Advanced Metering Infrastructure (AMI) system is a central access point for communication of information flows in the smart grid. There exits several alternative communication technologies for AMI networking [1-3], we presume to adopt a two-way communication for AMI based on the cognitive radio (CR) protocol IEEE 802.22. In CR protocols, we have the capability of recognizing the surrounding radio environments and operating in unused spectrum without causing harmful interference to primary users (PUs) [4]. In our framework PUs are anticipated to be television band (TV-B) users. Moreover, PUs are always 1st in the transmission queue so as to not be affected by unlicensed users. Unlicensed users are denoted as secondary users (SUs). In our framework, SUs that are AMI are labeled as A-SUs.

Key challenge for future CR based AMI networks to be addressed is the interference protection to the CR system in unplanned network scenario. Therefore, managing the available spectrum resources and share the resources among A-SU's (AMI-secondary user) under the constraint of coordinated spatial signatures require sophisticated sharing methods. In [5], the authors presented a scheduling strategy based on both maximizing system capacity and achieve fairness among SU, while minimizing the interference to the primary user. In [6], a cross-layer scheduling algorithm is evaluated by scheduling the users dynamically at each time slot based on the redefined QoS requirement, channel quality, service priority and also the interference caused by SU to the PU's receiver. The authors in [7] incorporate concept of soft frequency reuse with interference coordination scheme in existing conventional wireless networks. This interference coordination scheme presented in [8] scheme increase average cell throughput compared with existing schemes. However, the conventional wireless networks differ in numerous ways from our distribution-side smart grid communication networks. The availability of the frequency channels as well as the maximum power and data rate of the SUs widely depend on the PU activity and interference caused by SUs to PU's receiver.

In the aforementioned scheduling schemes, none of scheduling schemes considered the concept of maximum channel reuse which introduces new channels for scheduling, leading to higher channel efficiency and increasing the number of A-SUs accessing the CR channel. However, satisfying the interference constraints are within predetermined acceptable limits on a per A-SU location, per-time, and per-frequency basis.

In this paper, the interference aware scheduling (IAS) for dynamic channel allocation reuse, allows to allocate new channels in unplanned networks. Our model of channel reuse implies simultaneous use of intra cell physical resource elements (PRE) leading to dynamic co-channel interference on a per-PRE basis. This eliminates idle time-slots under the joint constraint of maximum interference and maximum capacity. We demonstrate that this approach substantially increases capacity gains by allocating more and more co-channels under the constraint of coordinated spatial signatures in MIMO systems for multi-cell environments.

Another distinguishing aspect of this paper is to analyze the smart meter network in a manner that jointly satisfies both the DOE smart grid communication protocol in terms of capacity and the IEEE 802.22 protocol satisfying the FCC CR requirements [9-10].

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II. SYSTEM MODEL

Fig. 1 illustrates the system model under consideration in this paper. As shown in Fig. 1, the system utilizes the CR scheme of IEEE802.22 WRAN. As shown in Fig. 1, the CR model assumes that the PU (e.g. television station transmitter denoted as PU) in the CR protocol has uncontested access to the channel. In addition, consumer premise equipment (CPE) indicates AMI denoted as SU in the CR protocol. Since the IEEE 802.22 WRAN specifies a fixed point-to-multipoint wireless air interface, BS can manage its own cell and all associated CPEs as shown in Fig. 1. As illustrated in Fig. 1, multiple cells are overlapped in IEEE 802.22. Since the IEEE 802.22 BSs and the CPEs operate in an opportunistic way in an unlicensed spectrum as stated earlier, *any additional coordination among cells of different service providers cannot be assumed*. Therefore, the CPEs of the other cells in the overlapped areas can be considered some uplink interferers to the BS in its own cell.

For the interference caused by a CPE located in the overlapped area of neighboring cells in Fig. 1, two cases can be considered. In Case I, the CPE is allocated with a channel that is available in both cells. We can also consider a 2nd Case II where the CPE is allocated to a channel that is available only in one cell that it has registered with, but not in the other cell (Case II). In Case I, the self-interference due to the neighboring cell can be suppressed using our beamforming approach. As indicated in the Case II, if the BS on one cell fails to detect the TV station's signaling the neighboring cell, some interference to TV users may occur in the neighboring cell. This case is often called hidden incumbent problem, which is one of serious issues in spectrum sensing for CR. To overcome the problem, the CPE on overlapped area can join the spectrum sensing, and send the detected data to the BS using a specific reporting channel [11]. Then, the BS can invoke a decision based upon fusion methods [12].

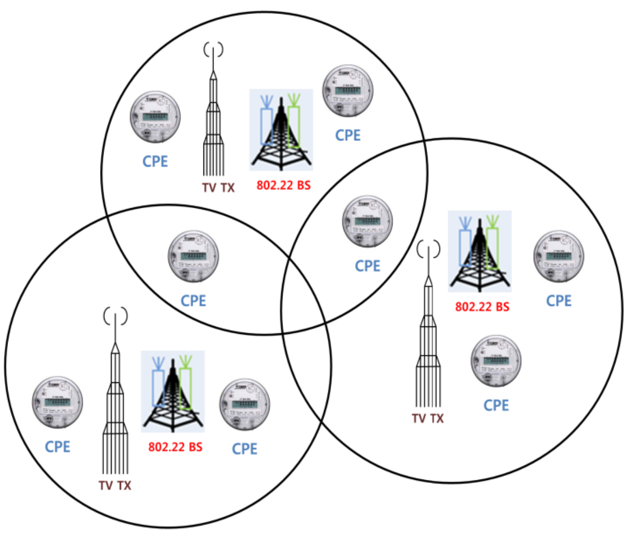

Fig. 1. The Cognitive Radio System Model

Radio resource management in our IEEE 802.22 based CR network model involves three dimensions: frequency, time and space. Physical resource element (PRE) spans in both frequency and time dimensions. We presume a scheduler coordinating the usage of PREs in adjacent cells by opportunistically leveraging multi-user AMI frequency, time and spatial diversity. It also ensures that PRE may be simultaneously assigned to more than one A-SU within each cell. By further assuming that orthogonally among sub-carriers can be adequately maintained, then intra-cell interference can be ignored between PU and SU. However, as previously mentioned if a PRE is simultaneously assigned to more than one A-SU meter it results in coordinated interference between A-SUs within the cell.

Fig. 2 shows the methodology for scheduling the PREs allocated to A-SUs. When PREs are reused, increased co-channel interference is traded off versus the allocation of additional frequency channels to unscheduled A-SUs. In Fig. 2, PU transmits over frequency *f3*; scheduled A-SU1 transmits over frequency *f1*; scheduled A-SU2 transmits over frequency f_2. We note that PU communication is disrupted if any user transmits data using frequency *f3* respectively. The system controls the interference power of the PUs to insure it remains below the maximum tolerable interference power. The diagram in Fig. 2 depicts that PUs that are unaffected. This is due to the fact that the A-SUs operate on orthogonal frequencies. However, it is possible that A-SU1 increases the co-channel interference to A-SU3 since they operate on same frequency *f*1. The main objective in this method is to determine the dynamic scheduling of PREs that maximizes channel reuse among A-SUs and maximized multi-user capacity considering both interference and noise of existing A-SU in that particular PRE.

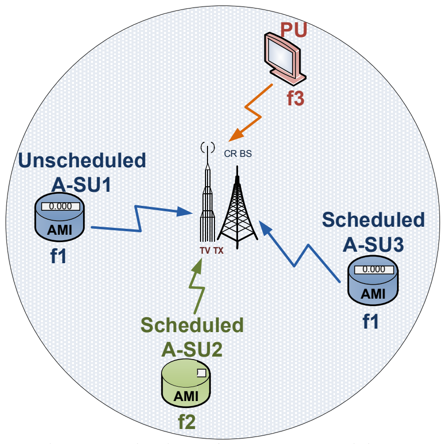

Fig. 2. Mechanism of our Reuse Model

III. INTERFERENCE –AWARE SCHEDULING ALGORITHM

We presume to leverage the approach presented in [13-14], which supports large scale and flexible infrastructure scenarios. As a main advantage of this approach, the smart grid application services and the communication platform services reside on the same infrastructure system [13-14]. Furthermore, the cloud server allocations can easily adjust with user demand profiles and variation. This applies to the application services for the smart grid and the communication platform services for wireless networking support. Other significant advantages of this approach are the ability of multi-user data (i.e. spatial location, channel information, etc.) to be available in the same cloud server, enabling joint optimization across scheduled users.

We presume the initial scheduling is performed on secondary users based on max rate algorithm (MRA) [15] or proportional fair (PF) [16]. $\overline{SU}$ is showing set of indices of all A-SUs within the cell as follow,

$$\overline{SU} = [su_1, su_2, ..., su_N] \quad (1)$$

where N is total number of A-SUs. $\overline{SU_s}$ is defined as the initial scheduled users through max–rate or PF algorithm and $\overline{SU_{us}}$ are unscheduled users. $\overline{SU_s}$ and $\overline{SU_{us}}$ are sub set of $\overline{SU}$,

$$\overline{SU} = \overline{SU_s} \cup \overline{SU_{us}} \quad (2)$$

Furthermore, the vector of fading coefficients for the channels between the SUs and CR BS are

$$\overline{H}_{SU}^{CBS}(k) = [h_1(k)...h_n(k)] \quad (3)$$

Fig. 3 depicts the proposed interference aware scheduling (IAS) algorithm. The scheduler selects active unscheduled users with data to send. We sort the $\overline{SU_{us}}$ by SINR in case of max-rate scheme or gamma (γ) [16] in PF scheme and channel coefficients in ascending order represented as $\overline{SU_{us}^{sort}}$. The ascending order ensures that A-SUs with high SINR or high gamma (γ) are available for maximum PRE reuse. We choose unscheduled A-SU as $\overline{SU_{us}^{sort}}(i), i = \{1..N_{us}\}$ from $\overline{SU_{us}^{sort}}$ with maximum SINR or gamma (γ) and higher channel coefficients as represented in step 4 in Fig. 3. We calculate the co-channel interference between $\overline{SU_{us}^{sort}}(i)$ and $\overline{SU_s}(j), j = \{1..N_s\}$. Where N_s and N_{us} are total number of scheduled and unscheduled A-SUs respectively. Choose the $\overline{SU_s}(j)$ with minimum co-channel interference with respect to $\overline{SU_{us}^{sort}}(i)$. Co-channel interference $I' = I_{\overline{SU_s}(j),\overline{SU_{us}^{sort}}(i)}$ is evaluated in the later part of the section. In step 7, we recalculate the capacity of $\overline{SU_s}(j)$ and $\overline{SU_{us}^{sort}}$ based on updated interference I' in step 5.

We presume for each A-SU, with index *i*, is serviced on k^{th} channel, the multiuser capacity for orthogonal OFDM signaling is given below and notes that it cannot exceed the Shannon capacity given as [17],

$$C_i = W_i \log_2(1 + \log_2(1 + h_i^2(k) SINR_i) \quad (4)$$

In real-world deployments, we can develop a modified Shannon capacity formula, by replacing the cell bandwidth, W_{cell} with an effective bandwidth and βW_{eff} [17] which accounts for G-factor dependencies and protocol control, pilot, and cyclic prefix overheads. Closely related to the SINR is the G-factor, which accounts for the geometric dependencies of cell layouts and dictates the statistics of the downlink capacity. The G-factor is the average own cell power to the other cell-power plus noise ratio when considering uniform spatial distributions of transceivers within a cell.

In addition, we can define a normalized effective signal to noise ratio, $SINR_{eff}$ adjust SNR for interference, G-factor and statistics. Defining the modified Shannon spectral efficiency for PU, as we therefore define the modified A-SU capacity in

$$C_i = \beta W_{eff_i} \log_2 \left(1 + \frac{\frac{h_i^2(k) SINR_i}{N+I}}{SINR_{eff}} \right) \quad (5)$$

where $SINR_i$ is the signal to interference plus noise power ratio for i^{th} A-SU. Therefore $SINR_i$ can be expresses as

$$SINR_i = \frac{P_{r_i}}{\sigma_N^2 + \sigma_I^2} \quad (6)$$

where P_{r_i} , σ_N^2 , and σ_I^2 denote the received signal power from i^{th} A-SU, the noise power, and the self-interference power at the CR base station in the cell.

Using equation 5 we calculate capacity of $\overline{SU_s}(j)$ and $\overline{SU_{us}^{sort}}(i)$ as labeled as $C'_{\overline{SU_s}(j)}$ and $C'_{\overline{SU_{us}^{sort}}(i)}$. $C'_{\overline{SU_s}(j)} < C_{\overline{SU_s}(j)}$, is due to effect of increase in interference caused due to PRE reuse. The objective of the IAS algorithm is to maximize the reuse of PRE and improve the capacity while optimally exploiting the interference variations occurred. This necessitates verifying the following condition:

$$C' = C'_{\overline{SU_{us}^{sort}}(i)} + C'_{\overline{SU_s}(j)} \quad (7)$$

$$C' > C_{\overline{SU_s}(j)} \quad (8)$$

However, the other critical factor to be taken in consideration is maximum tolerable interference I_{th} . We need to check the co-channel interference $I' = I_{\overline{SU_s}(j),\overline{SU_{us}^{sort}}(i)}$ observed should be always less than I_{th} in order satisfy QoS factor and FCC requirements [10].

$$I' < I_{th} \quad (9)$$

In step 9, we check the conditions stated in (8) and (9). If conditions are satisfied scheduler allows $\overline{SU_{us}^{sort}}(i)$ reusing the same PREs of $\overline{SU_s}(i)$ and updates the $\overline{SU_{us}}$ and $\overline{SU_s}$ shown in step 11 and iterates the process until all $\overline{SU_{us}}$ are empty. If the conditions are not satisfies, we updated the $\overline{SU_{us}}$ as seen in step 12 and we iterates the process to step 3.

A. Interference Model for SISO

The OFDM transmission system with MIMO model for an A-SU as a function of sub carrier K is given by,

$$\boldsymbol{Y}(k) = \boldsymbol{H}_{n_T \times n_R}(k)\boldsymbol{X}(k) + \boldsymbol{N}(k) + \boldsymbol{I}(K) \tag{10}$$

In (10), $\boldsymbol{Y}(k) = [Y_1[k],...,Y_{N_T}[k]]$ is the received signal on the kth subcarrier in CR base station. $\boldsymbol{H}_{n_T \times n_R}(k) = [H_1[k],...,H_{N_T}[k]]$ is the channel coefficients. In SISO, n_T=1 and n_R=1; $\boldsymbol{X}(k) = [X_1[k],...,X_{N_T}[k]]$ denotes vector of transmit data at kth subcarrier in CRBS from the transmitted OFDM signal in uplink model.

The interference $\boldsymbol{I}(K)$, is coordinated interference generated from reuse of PREs and self-interference from users of other cells in the overlapped area at frequency index of k (e.g. subcarrier) for the antenna of CRBS in SISO and MIMO model. Thus $I_j(k)$ is the total aggregated interference with $\overline{SU}_s(j)$,

$$\boldsymbol{I}_j(k) = \underbrace{\sum_{n_T}\sum_{i=1}^{N_{ns}} H^{i,j}_{n_T \times n_R} x_{\overline{SU^{sort}_{us}}(i)}(k)}_{\zeta_k} + \underbrace{\sum_{n_T}\sum_{l} H^{l,j}_{n_T \times n_R} x_l(k)}_{\psi_k} \tag{11}$$

The desired the received signal at CRBS is distorted by coordinated interference aggregated in ζ_k and uncoordinated interference in ψ_k. In (11), Nns is the total number of scheduled users from $\overline{SU_{us}}$ based on IAS algorithm. Simulation results will be presented in section IV.

B. Interference Model for MIMO Systems

The multi-antenna system offers well known motivations compared to conventional wireless communication systems. Our attention in this paper is focused on smart meter equipped with multi-antenna systems. Performance can be enhanced and capacity maximized when perfect or partial channel state information (CSI) is made available at the transmitter [16]. This presumption applies well to AMI networks with fixed spatial location and wireless channels with zero Doppler.

We find Eigen-mode beam forming (BF) attractive due to its yielding of higher throughputs even in low SINR regions, where coordinated and uncoordinated interference is likely high in these scenarios [19]. The beam forming approach is based on single value decomposition (SVD) in multi-antenna based smart grid systems.

We consider n_T transmit antennas, generating a baseband signal vector $\overline{A}_{Tx} = [x........x]^T$. Without loss of generality we also assume n_R receive antennas, $\overline{A}_{Rx}$, for a $n_T \times n_R$ MIMO system.

Denoting the singular value decomposition (SVD) of the channel matrix as, $H = U\Lambda V^H$ and the largest eigenvector of the left hand and right hand side SVD unitary matrices U and V, respectively as $\overline{u}_{\max}$ and $\overline{v}_{\max}$. The singular value matrix is

$$\Lambda = Diag(\overline{\sigma}) = \begin{pmatrix} \sigma_0 & 0 & 0 \\ 0 & \ddots & 0 \\ 0 & 0 & \sigma_{\max} \end{pmatrix} \tag{12}$$

Where $\sigma_{\max}$ is the square root of the largest eigenvalue of HH^H. The receive noise vector at the n_R receive antennas is $\overline{N}$. The detector output, y is described by the beamforming equation

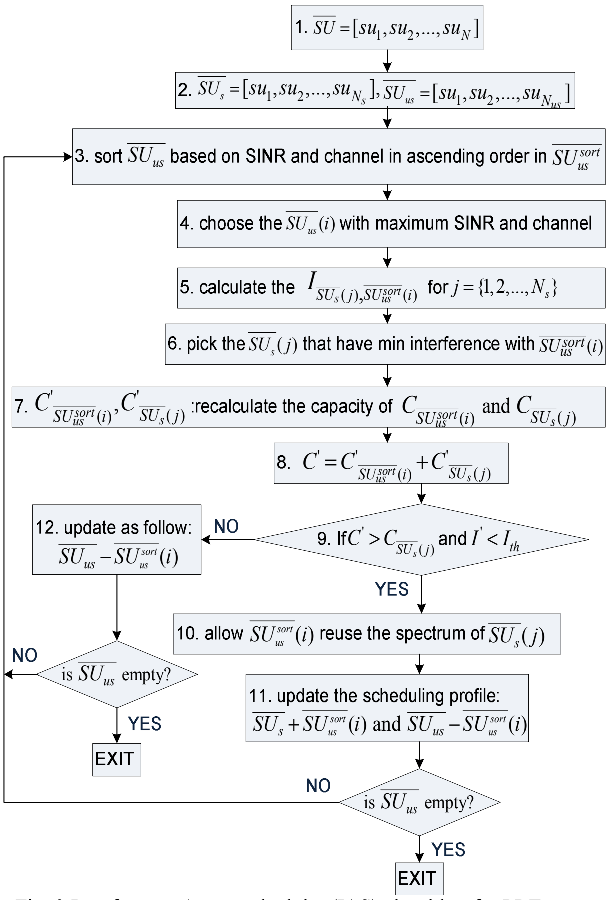

Fig. 3.Interference-Aware scheduler (IAS) algorithm for PRE reuse

$$\boldsymbol{y} = \underbrace{\left(u^H_{\max}\right)}_{Decoder}\left(\underbrace{Hv_{\max}Ix}_{\Pr ecoder} + \overline{N}^T + \underbrace{\sum_{l=1}^{N_{ns}} H_l \overline{v}_l I x_l}_{Interference}\right) \tag{13}$$

$$\boldsymbol{y} = x\sigma_{\max} + \underbrace{\overline{U}^H_{\max}\overline{N}^T}_{RxNoise} + \underbrace{\overline{U}^H_{\max}\sum_{l=1}^{N_{ns}} H_l \overline{V}_l I x_l}_{\phi_k} \tag{14}$$

ϕ_k is coordinated interference in beamforming model. By using that, the total aggregated interference ($\boldsymbol{I}^{BF}_j$) with $\overline{SU}_s(j)$ in beamforming is

$$\boldsymbol{I}^{BF}_j(k) = \varphi_k + \underbrace{\sum_{n_T}\sum_{l} H_{n_T \times n_R}{}^{l,j} x_l(k)}_{\psi'_k} \tag{15}$$

where ψ'_k is uncoordinated interference in BF model.

IV. SIMULATIONS AND RESULTS

Through simulations, we evaluate the performance of the proposed scheme for unplanned networks. Numerical results exhibit the effectiveness of the proposed interference-aware scheduler for the SISO and MIMO smart meters. In this simulation, we follow the IEEE WRAN standard [20] as OFDM parameters. We consider one of the possible antenna configurations in the 4G standards, in MIMO scenario we presume to have 4 transmit and 4 receive antennas. To minimize the change to the existing 4G systems, we consider using only antennas for the multiple dimensions, i.e., M = 4.

TABLE I
THE OFDM PARAMETERS FOR IEEE802.22 WRAN

Channel bandwidth (MHz)	6
Number (*N*) of subcarriers for FFT	2048
Number of data subcarriers for FFT	1440
Number of pilot subcarriers for FFT	240
Subcarrier spacing (KHz): PRE BW	3.348
Modulation	QPSK

TABLE II
THE POWER-DELAY PROFILE OF PROFILE A CHANNEL

Profile A	Path1	Path2	Path3	Path4	Path5	Path6
Excess delay (us)	0	3	8	11	13	21
Relative Power (dB)	0	-7	-15	-22	-24	-19

TABLE III
PARAMETERS FOR SIMULATION ANALYSIS

Cell radius (Km)	30
Carrier frequency (MHz)	599
Channel availability (α)	0.5
Total number of channels (NCR)	60
Channel bandwidth (MHz)	6
Number of AMIs (KCR)	90
Thermal noise (dBm/Hz)	-174

In the simulation, we follow IEEE 802.22 for smart grid systems as given in Table I. In the simulation, the WRAN for smart grid systems is assumed to operate at 599 MHz which belongs to the VHF/UHF TV broadcast bands. In addition, the profile A channel [21] is considered the frequency-selective fading channel for the WRAN in this simulation. Table II shows the power-delay profile (PDP) for the profile A channel. Table III also shows the parameters for capacity analysis.

Fig. 4 shows throughput performance of A-SUs as function of SNR. We assume that number of A-SU are 20 in the cell. We employ our MIMO- IAS scheme provides significant gain over the max-rate scheduling scheme in downlink scenario scenario. The proposed method exploits both opportunistic and dynamic channel reuse allocation and adaptively dependent on network environments, and hence achieves the highest downlink capacity in the limited spectrum requirements. Similarly, our proposed SISO-IAS scheme also achieves a higher gain over the conventional max-rate scheduling scheme in downlink scenario. On the contrary, since the uplink channel has more strict transmission power constraints, the IAS scheme does not help to improve its total spectral efficiency as much as that of downlink as shown in Fig.5. Fig.4 and Fig.5 shows that the average capacity for each scheduled A-SU satisfies the DOE smart grid communication protocol average capacity requirements [10].

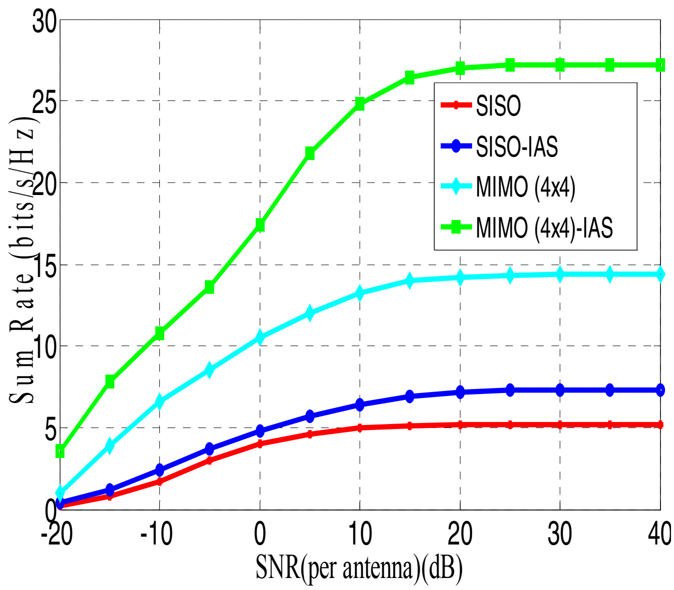

Fig. 4. Performance comparison in spectral efficiency:Downlink

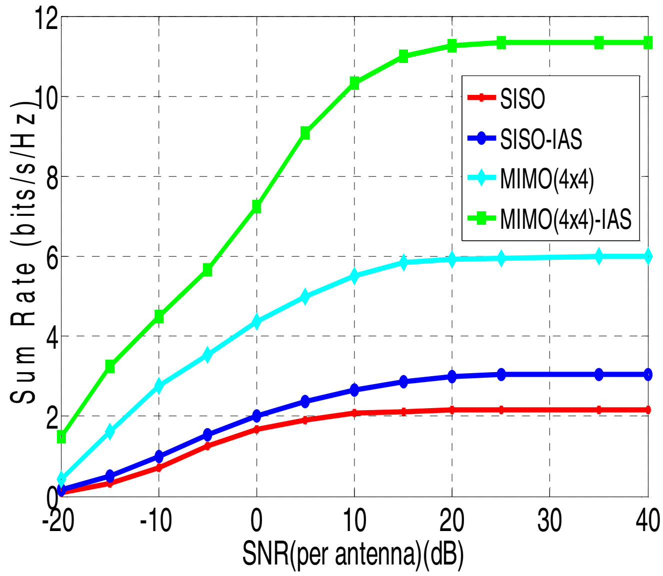

Fig. 5. Performance comparison in spectral efficiency: Uplink

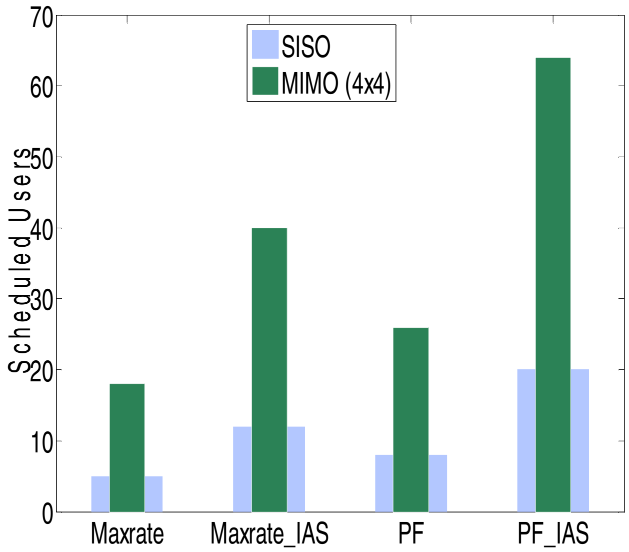

Fig.6. Average number of A-SU scheduled per one TTI in SISO and MIMO scenario applying IAS on existing max-rate and propotional fair (PF) algorithms

Fig. 6 and shows the average number of users scheduled per one Transmission Time Interval (TTI) when 75 A-SUs are active in a cell and around 20% of idle resources elements (RE) are available. We can see that in SISO scenario at least 12 and 20 A-SUs are scheduled to idle REs by employing IAS algorithm on conventional PF scheme. In this MIMO case, as one can expect, our IAS scheme provides at least 25 and 64 A-SUs are scheduled to idle REs by employing IAS algorithm on conventional PF scheme.

V. CONCLUSION

We address that the novel IAS scheduling protocol ideally suited for maximum channel reuse in unplanned networks. We analyze the application of SISO (single-input and single-output) and MIMO (multiple-input and multiple output) interference aware scheduling to maximize the capacity and number of scheduled smart meters. The numerical results show that the performance for IAS with MIMO and SISO has significant capacity increase, larger than that for the case of max rate at received SINR. Much larger gains occur as the antenna array size increases. Our technique also shows even greater performance increase in scheduling no of secondary users, larger than that for the case of proportional fair scheme. Finally, our capacity analysis reveals that the IEEE 802.22 protocol enabling FCC-CR can support future distributed smart grid communication network comprised of smart meters.

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