Quality of Service Assurance-based Auction for Spectrum Sharing Systems

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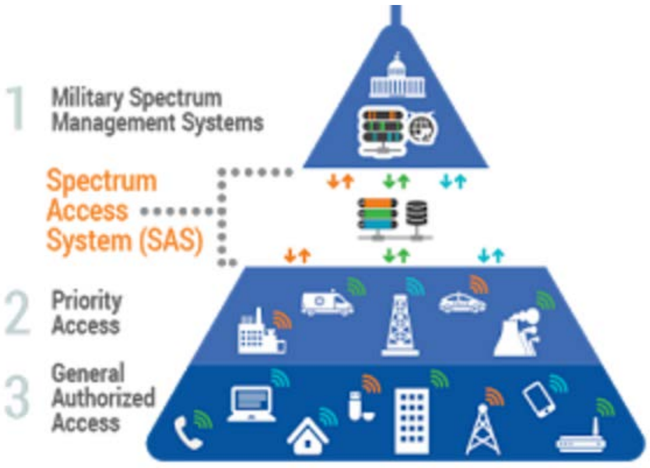
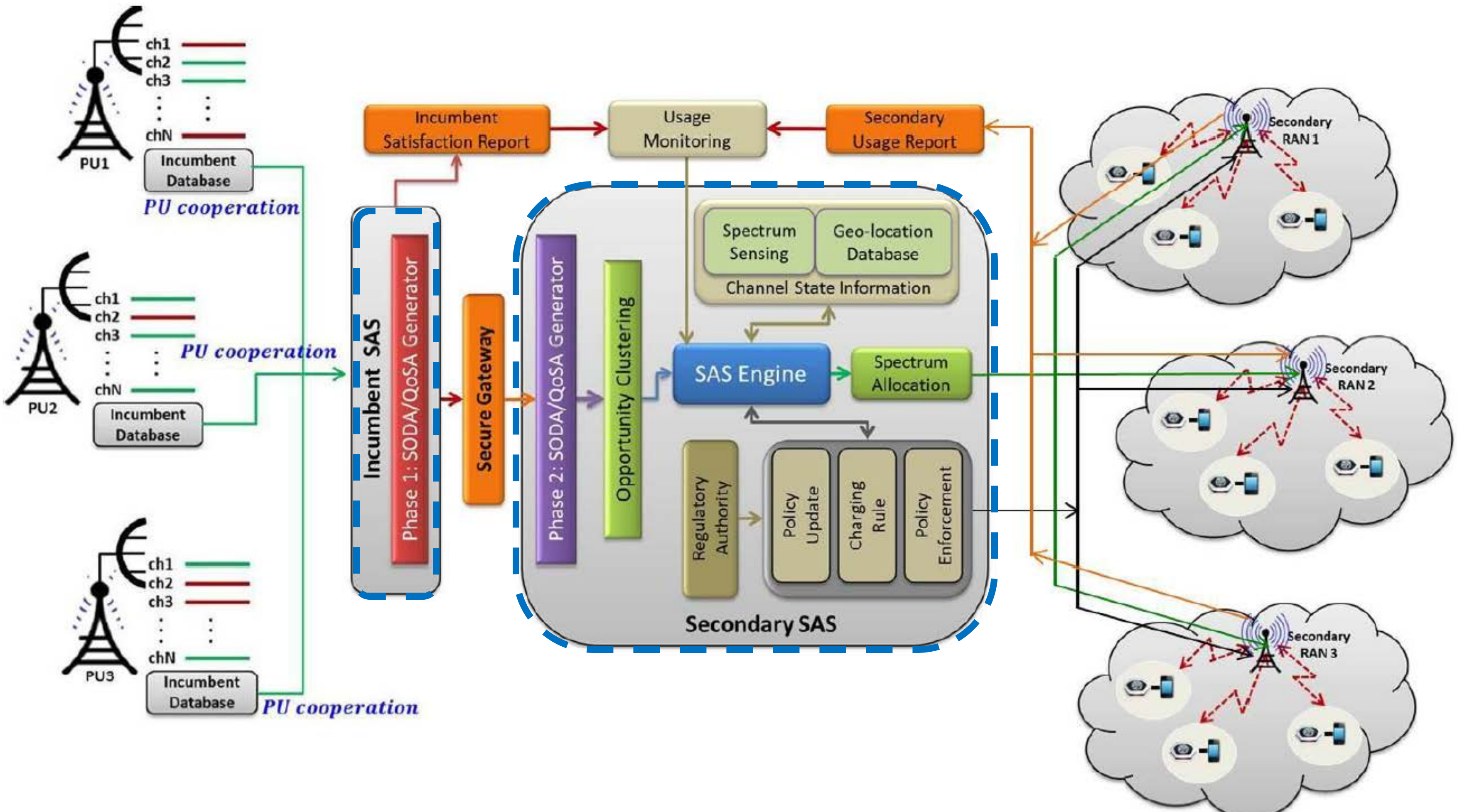
This work is supported by the National Science Foundation (NSF) under grant number 1343222.

Introduction

- Objective:
  - Explore the impact of PU-SU Cooperation on spectrum opportunity management
- Proposed Solution:
  - Use QoSA values to evaluate the quality of the opportunities
    - Spectrum opportunity auctioning
    - Spectrum opportunity allocation
- Problem statement:
  - Primary-Secondary Cooperation
    - Improve spectrum opportunity auctioning
    - Improve dynamic resource allocation



PU-SU Cooperation Framework



Opportunity Clustering with Spectrum Opportunity Duration

- The normalized effective duration in terms of QoSA $\alpha = \frac{QoSA-1}{\ln(QoSA)}$
- Applied to measure the quality of channel

QoSA Calculation Procedure

- Phase-1: Incumbent SAS
  - Access PU database and/or Environmental Sensing Capability (ESC) results
  - Get previously stored PU usage information
  - **Train the NS-HMM model parameters**
- Phase-2: Secondary SAS
  - Receives estimated model parameters from I-SAS
  - Uses current channel monitoring results
  - **Predict the availability and duration of spectrum opportunities**

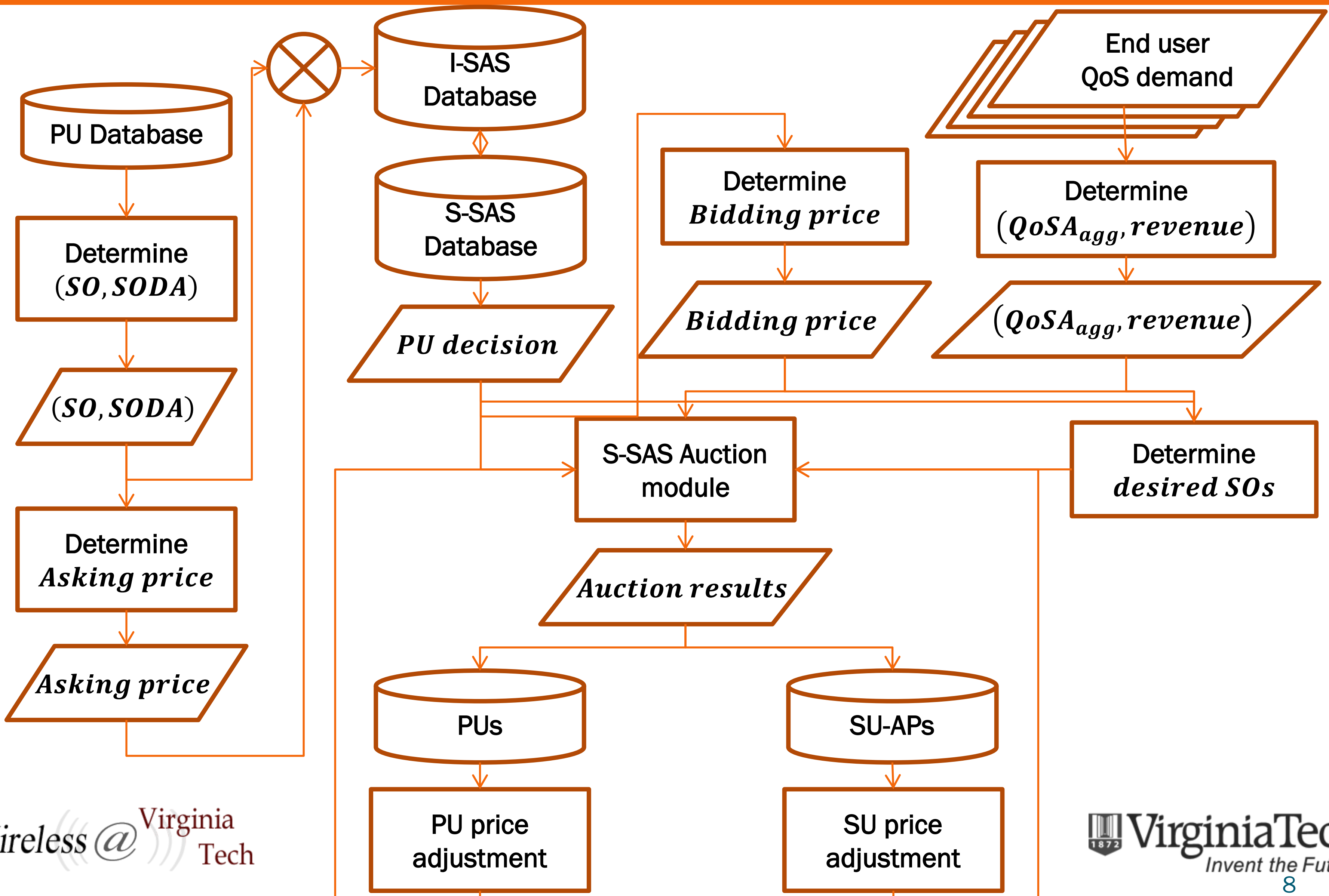
Spectrum Opportunity Auctioning considering the Probabilistic Assurance

- An auction-based spectrum sharing framework
  - Accounts for the quality of the available spectrum opportunity
    - The probabilistic assurance generated by the SAS
- PU and SU operations
  - Adjust their evaluation of the available opportunities over time
  - Achieve a price combination that maximizes both the PU and SU objective

Proposed Solution

- PUs determines the opportunities and asking prices
- I-SAS determines the SODA values for the opportunities
- SU-APs determine the aggregate QoS demand
- SU-APs determine the bidding price
- S-SAS determines the winning bids
- PUs adjust asking prices based on the auction results
- SU-APs adjusts bidding prices for unassigned channels

Proposed Solution (Continued)



Problem Formulation

- SU-AP tries to solve the following problem

$$\max_{I} \quad P_j = \sum_{l=1}^{L}\sum_{i=1}^{M}(r_j - c_{i,j,l})k_{i,j}\alpha_l B\tau I_{j,desired_{l,i}}$$

$$s.t. \quad \sum_{l=1}^{L}\sum_{i=1}^{M} k_{i,j}\alpha_l B\tau I_{j,desired_{l,i}} \geq Q_{agg_j}$$

P: SU payoffs
L: number of opportunity clusters
r: revenue per opportunity
c: bidding price
k: spectral effeciency
α: effective opportunity duration
Q_{agg}: Aggregate QoS demand
$I_{desired}$: desired opportunities

- The objective of each SU is to find the optimal bidding price per unit while
  - Maximize the payoff function (revenue per SU)
  - Satisfy the aggregated QoS demand
- Can be reduced to binary integer programming problem

Auction Algorithm

Goal: generate allocation indicator information for given SU bidding price

- Spectrum opportunity clusters: $\boldsymbol{SO}$: $\{(x_{il}\theta_{il},\ \alpha_l),\ \forall i,l\}$; SU demand for each cluster: $\boldsymbol{SU_D}$: $\{I_{jl} \in (1,0), \forall j,l\}$; SU bidding price for each cluster: $\boldsymbol{SU_P}$: $\{y_{jl},\ \forall j,l\}$
- Auction decision set: $\boldsymbol{I_{allocated}}$: $\{I_{ijl} \in (1,0), \forall i,j,l\}$
- If any channel has a single claim:

$$\boldsymbol{SO}: \{(x_{il}\theta_{il}, \alpha_l)\} \rightarrow \boldsymbol{I_{allocated}}: \{I_{ijl} \in (1,0)\}$$

- If any channel has multiple claims:

$$\boldsymbol{find}\ j^* = \arg \max_{\forall j \in \{I_{jl}=1\}} \boldsymbol{SU_P}: \{y_{jl}, \forall i,l\}$$

$$\boldsymbol{SO}: \{(x_{il}\theta_{il}, \alpha_l)\} \rightarrow \boldsymbol{I_{allocated}}: \{I_{ij^*l}\}$$

$$\mathbf{0} \rightarrow \boldsymbol{I_{allocated}}: \{I_{ijl}\}, \forall j \in \{1,2,\ldots,L; j \neq j^*\}$$

- **S-SAS forwards the allocation indicator information**, $\boldsymbol{I_{j,allocated}}$: $\{I_{ijl} \in (1,0)\}$, to each of the participating SU-APs

Price Adjustment Algorithm

Goal: adjust the price for given channel auction result

- S-SAS generate list of unassigned channel and forwards $\boldsymbol{I_{unassigned}}$ to I-SAS:

$$\boldsymbol{for}\ \forall l,i, \qquad if(SO_{il} \notin \boldsymbol{I_{allocated}}): SO_{il} \rightarrow \boldsymbol{I_{unassigned}}$$

- I-SAS in consultation with the corresponding PU adjusts the discount factor θ_{il}

$$\boldsymbol{for}\ \forall l,i \in \boldsymbol{I_{unassigned}}, \qquad \theta_{il}^{new} = \theta_{il} - \Delta_{PU_{il}}:\ \theta_{il}^{new} \rightarrow \boldsymbol{SO}(x_{il}\theta_{il}^{new}, \alpha_l)$$

- The SU-AP calculates the loss in revenue due to the current bidding price

$$\boldsymbol{for}\ \forall l,i \in \boldsymbol{I_{j,desired}}, \qquad P_{j_{achievable}} = \sum_{l=1}^{L}\sum_{i=1}^{M}(r_j - c_{i,j,l})k_{i,j}\alpha_l B\tau \boldsymbol{I_{j,desired}}$$

$$\boldsymbol{for}\ \forall l,i \in \boldsymbol{I_{j,allocated}}, \qquad P_{j_{achieved}} = \sum_{l=1}^{L}\sum_{i=1}^{M}(r_j - c_{i,j,l})k_{i,j}\alpha_l B\tau \boldsymbol{I_{j,allocated}}$$

$$\left(P_{j_{missed}} = P_{j_{achievable}} - P_{j_{achieved}}\right):\ \Delta_{SU_{jl}} = \theta_{adjust} P_{j_{missed}}$$

$$y_{jl}^{new} = y_{jl} + \Delta_{SU_{jl}}$$

- The SU-AP that gets allocated its desired channels does not perform the price adjustment mentioned in Step2

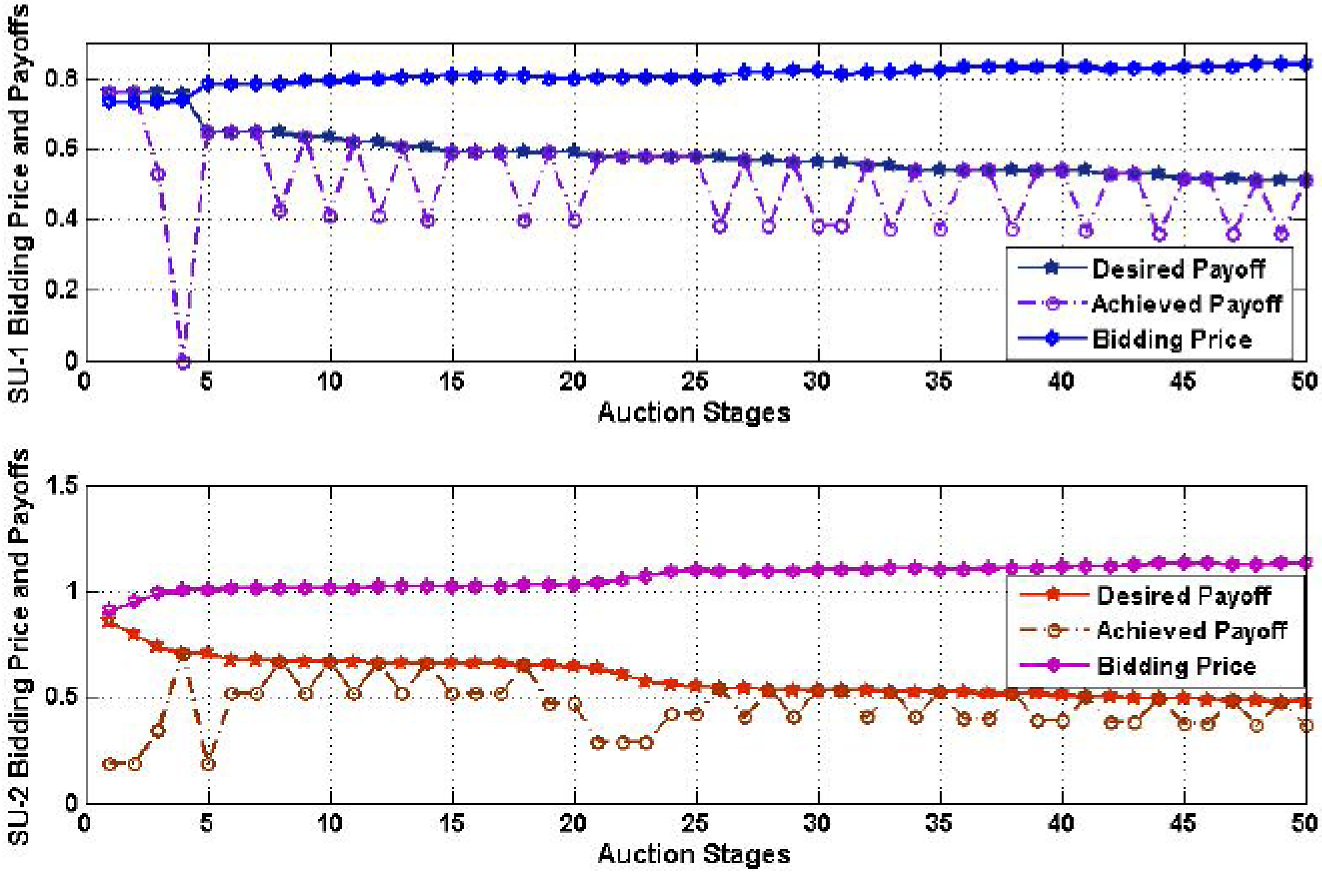
$$\boldsymbol{for}\ \forall l,i, \qquad if(\boldsymbol{I_{desired}} = \boldsymbol{I_{allocated}}): \Delta_{SU_{jl}} = 0;\ y_{jl}^{new} = y_{jl}$$

Simulation Parameters

Category	QoSA Range	Cluster QoSA	*α value*
A	$QoSA > 0.8$	0.9	0.9491
B	$0.6 > QoSA \geq 0.8$	0.7	0.8411
C	$0.4 > QoSA \geq 0.6$	0.5	0.7213
D	$0.4 \geq QoSA$	0.3	0.5814

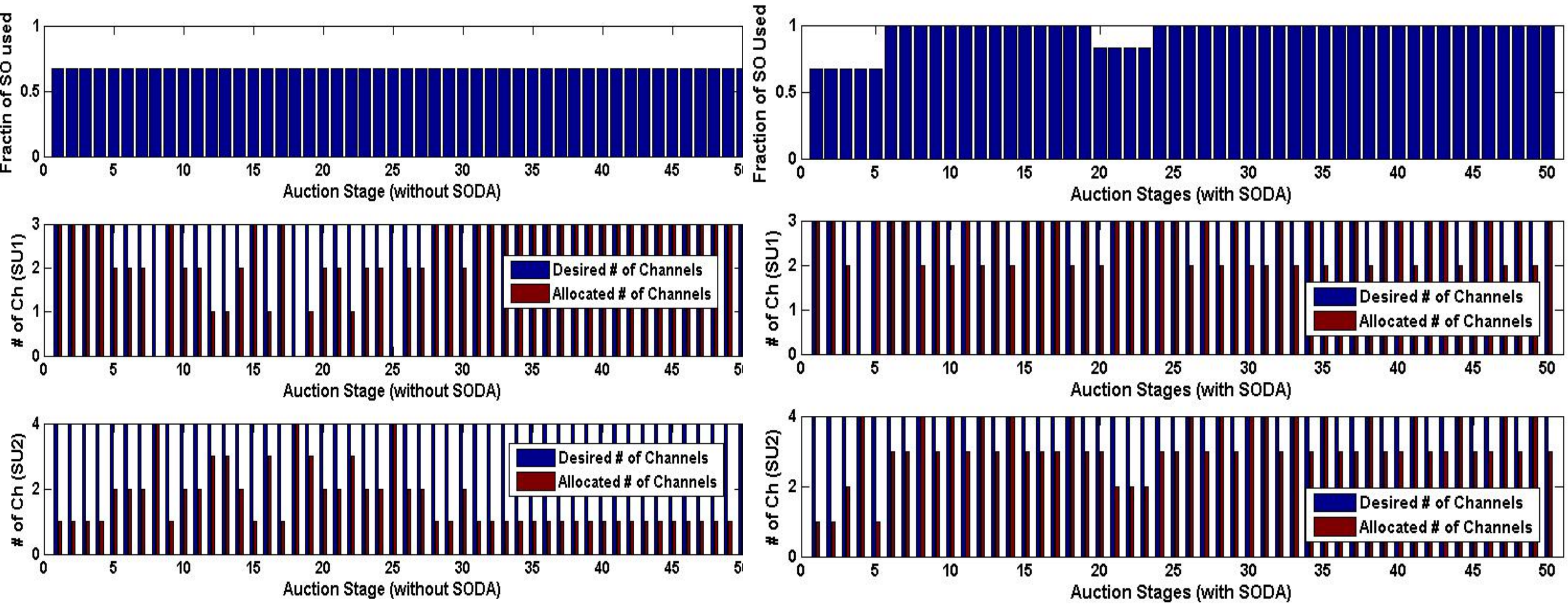
# of PUs M =2
# of SUs N =2
PU BW =10MHz×3
Duration =1 unit
# of cat. = 4
Initial Price= 1 unit (PU-1)
= 0.8 unit (PU-2)

SU-AP Bidding Prices and Corresponding Payoffs



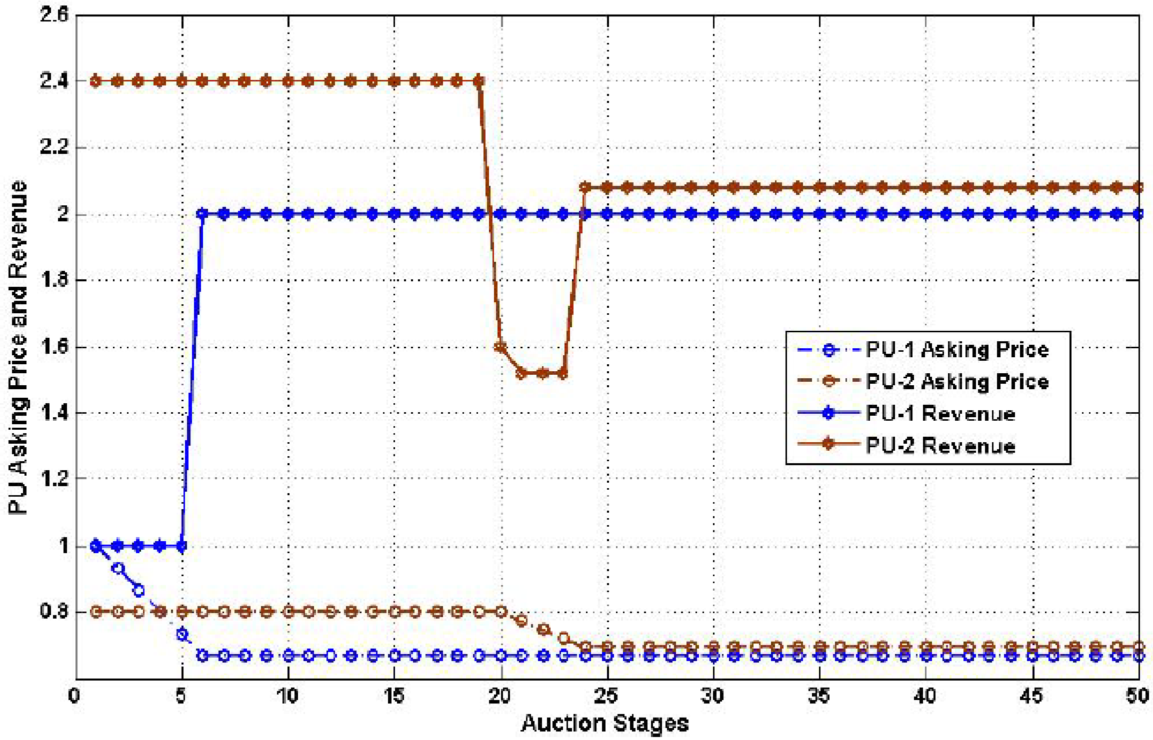
- The iterative adjustments in the bidding prices help the SU-APs to achieve payoffs.

SU-AP Channel Allocation and Overall Spectrum Usage



- The iterative price adjustment from both the PU and SU-APs helps the fair auction
- Approximately 60% of the spectrum opportunities are allocated to the SU-APs at stage 1
- All the available spectrum opportunities are allocated to the SU-Aps at later stages

PU Asking Price and Revenues



- The revenue generated by PU1 is much lower compared to PU2 at beginning
- PU1 identifies the problem and adjusts its asking price
- The revenue earned by PU1 improves significantly by the auction stage 6
- PU2 readjusts its asking price at stage 20

Conclusion and Future Works

- We proposed an auction-based spectrum sharing framework includes the spectrum opportunity duration information
- We proposed an iterative auction algorithm that quality of the spectrum opportunities is decided
- The proposed approach improved the percentile of the available spectrum opportunities used by the SUs
- SODA values allow estimation of effective opportunity duration
  - Achievable QoS from the opportunities can be determined
- SUs request opportunities to meet their QoS demand
  - Translating QoS demand for dedicated channel to equivalent group of opportunities