

GENESIS: Green Energy Efficiency Optimization in Integrated Sensing and Communication Networks

Arianna Santamaria Penafiel*, Md Sadman Siraj*, Eirini Eleni Tsiropoulou*, and Symeon Papavassiliou†
 {ari, mdsadmansiraj96, eirini}@unm.edu, papavass@mail.ntua.gr}

* Dept. of Electrical and Computer Engineering, University of New Mexico, Albuquerque, NM, USA

† School of Electrical and Computer Engineering, National Technical University of Athens, Athens, Greece

Abstract—In the emerging landscape of Integrated Sensing and Communication (ISAC) networks, achieving energy efficiency while concurrently performing sensing and communication tasks remains challenging. This paper introduces the GENESIS framework, a novel solution that empowers User Equipment (UEs) to make informed decisions regarding their transmission power allocation, optimizing the energy efficiency of sensing, communication, and data reporting to the gNB (gNodeB) functions. Initially, a novel ISAC network paradigm is proposed, where the gNB employs rewards, such as monetary incentives, to motivate UEs to engage in sensing, data collection, and reporting within its coverage area based on the principles of Contract Theory. The proposed GENESIS framework integrates the incentive mechanism with an optimal resource management technique which facilitates UEs to make energy-efficient decisions that balance their dual roles of sensing and communication, distributedly, while maximizing overall energy efficiency. The resulting multi-variable resource management problem is formulated as a non-cooperative game, establishing the existence and uniqueness of a Nash Equilibrium. Through modeling and simulation, we demonstrate GENESIS benefits, showcasing its energy-efficient operation and rapid convergence to optimal operational points.

Index Terms—Integrated Sensing and Communication, Contract Theory, Game Theory.

I. INTRODUCTION

ISAC networks offer a promising solution for future wireless networks by integrating infrastructure and signals, reducing costs, and enhancing spectral efficiency and energy optimization [1]. ISAC enables high-precision sensing and communication services by sharing resources, however the potential of the joint sensing and communication functionalities in User Equipment (UE) for effective resource management remains underexplored, with the existing literature mainly focusing in a fragmented manner on one of the two functionalities [2]. In this paper, we introduce the GENESIS framework, a decentralized resource management framework for UEs, with two key objectives. Firstly, it defines the appropriate amount of data that the UEs should sense and collect by introducing an innovative contract-theoretic incentivization system. Secondly, GENESIS optimizes the transmission power levels and power allocation between sensing and communication functionalities in UEs, all geared toward maximizing energy efficiency within the ISAC network.

This research was supported in part by the NSF CNS # 2219617 and NSF ECCS #2319994 awards.

A. Related Work

Considerable efforts have been devoted to resource management problems in the downlink of ISAC networks, particularly in terms of gNBs (next-generation Node B) which can act as sensing nodes. In [3], a power allocation algorithm is proposed for a centralized cell-free massive Multiple-Input Multiple-Output (MIMO) ISAC system, enhancing target detection. In [4], a MIMO ISAC system is studied for various target scenarios, analyzing the tradeoff between sensing performance and communication data rate. In [5], a micro base station is used for simultaneous target sensing and cooperative communication, with non-orthogonal downlink transmission to improve spectrum utilization and overall performance. In [6], the authors explore a UAV-enabled ISAC system, optimizing UAV trajectory and transmit beamforming for communication throughput and sensing beamforming gain. In [7], a secure pilot allocation method is proposed to protect channel state information (CSI) in ISAC networks, preventing malicious access to critical target information through CSI-based sensing.

The academia and industry have both increasingly focused on the challenges of resource management within ISAC networks [8]. In [9], the authors optimize the subcarrier allocation and transmission power in ISAC networks to minimize power while ensuring quality in sensing and communication. In [10], the proposed approach optimizes the power and bandwidth allocation in ISAC networks to improve target localization accuracy while maintaining communication Quality of Service (QoS). In [11], the correlated communication and sensing channels are examined to enhance communication capacity through sensing-assisted beam alignment and location estimation, while in [12], the Reconfigurable Intelligent Surfaces are used in Non-Orthogonal Multiple Access (NOMA) ISAC networks to improve radar sensing by optimizing beamforming and power allocation.

B. Contributions and Outline

In the realm of ISAC networks, optimizing UEs' energy efficiency during simultaneous sensing and communication tasks is a largely unexplored challenge. Existing research mainly focus on optimizing the energy efficiency of either sensing or communication functionalities within ISAC networks, in an isolated manner. This paper presents the GENESIS framework, a decentralized resource management system for the UEs,

with dual goal: determining the optimal data collection and introducing a contract theoretic-based incentivization mechanism, along with optimizing power allocation for sensing and communication to enhance energy efficiency in ISAC networks. The main contributions of the paper are:

- 1) A novel ISAC network is introduced, where the gNB participates in a non-cooperative game with each UE to provide appropriate rewards (e.g., monetary rewards) to the UEs to incentivize them to sense, collect, and report data from targets residing in its coverage area. The proposed incentivization mechanism follows the Spence's model under the principles of Contract Theory [13].
- 2) The GENESIS framework is introduced incorporating the Spence's model incentivization mechanism and an optimal resource management approach to determine the UEs' optimal uplink transmission power and power splitting among the sensing and communication operations. The GENESIS framework enables each UE to distributedly maximize its overall experienced energy efficiency.
- 3) The optimal multi-variable resource management problem is formulated as a non-cooperative game among the UEs, using as input the amount of data that each UE has already been incentivized to collect and report to the gNB, and the existence and uniqueness of a Nash Equilibrium has been derived.
- 4) The GENESIS framework is evaluated through a detailed set of simulation-based experiments demonstrating: (i) its benefits in terms of its energy efficient operation and fast convergence to the optimal solution; and (ii) its superiority compared to existing data rate optimization resource management approaches in ISAC networks.

In the rest of the paper, Section II presents the UEs' incentivization mechanism, while the GENESIS framework is analyzed in Section III. Section IV presents the numerical evaluation and Section V concludes the paper.

II. INCENTIVES FOR SENSING IN ISAC

We consider a set of UEs $\mathcal{N} = \{1, \dots, n, \dots, N\}$ who are capable of joint sensing and communication operations and a gNB that collects sensing data and supports the UEs' communication service. The UEs are grouped into two main categories: H (High) or L (Low), based on their sensing capability which is determined based on the available targets in the UEs' proximity. Each UE can provide e_n^L [bits], $\forall n \in \mathcal{N}_L \subseteq \mathcal{N}$ or e_n^H [bits], $\forall n \in \mathcal{N}_H \subseteq \mathcal{N}$ with $\mathcal{N}_L \cup \mathcal{N}_H = \mathcal{N}$, sensing data by the waveforms reflected on the surrounding targets. Each UE's goal is to determine the optimal amount of reported sensing data to the gNB while receiving a corresponding incentivization reward $r_H > r_L[\frac{c}{bits}]$ from the gNB. The optimal amount of sensing data is: $\hat{e}_n^L = e_n^L + e_n^{L*}$ and $\hat{e}_n^H = e_n^H + e_n^{H*}$, if the UE belongs to the L or H category, respectively, where e_n^{L*} , e_n^{H*} [bits] is the additional amount of data that the user is willing to collect for a corresponding reward r_L , r_H , respectively, and an experienced cost $c(e_n^{L*}) = \theta_L e_n^{L*}$, $c(e_n^{H*}) = \theta_H e_n^{H*}$, with $\theta_H < \theta_L[\frac{c}{bits}]$,

in order to move closer to the targets and collect more sensing data. In Contract Theory, this model is known as Spence's model and it revolves around higher-tier users having lower experienced costs [13].

A game is formulated between the gNB and each UE, considering incomplete information from the gNB's side regarding each UE's potential to provide sensing data. In the first stage of the game, each UE $n \in \mathcal{N}$ selects randomly a feasible amount of data $\hat{e}_n^{H/L}$ that can provide to the gNB to maximize its expected return based on its sensing capabilities. Let $P_{H/L}(\hat{e}_n^{H/L})$ denote the probability that the UE of type H/L chooses to collect and reports $\hat{e}_n^{H/L}$ data to the gNB. In the second stage of the game, the outcome is entirely driven by how the gNB's beliefs have been affected by the observation of the UEs' amounts of reported sensing data. Let $\beta(\theta_{H/L}|\hat{e}_n^{H/L})$ denote the gNB's revised beliefs regarding the amount of reported sensing data upon observing $\hat{e}_n^{H/L}$. Then, the equilibrium reward in the second stage of the game is: $W = \beta(\theta_H|\hat{e}_n^H)r_H + \beta(\theta_L|\hat{e}_n^L)r_L[\frac{c}{bits}]$, with $\beta(\theta_L|\hat{e}_n^L) = 1 - \beta(\theta_H|\hat{e}_n^H)$.

Definition 1: (Perfect Bayesian Equilibrium) A Perfect Bayesian Equilibrium (PBE) is a set of strategies $\{P_{H/L}(\hat{e}_n^{H/L})\}$ for the UEs' types and conditional beliefs $\beta(\theta_{H/L}|\hat{e}_n^{H/L})$ for the gNB such that:

- 1) All amounts of reported sensing data $\hat{e}_n^{H/L*}$ observed with positive probability $P_{H/L}(\hat{e}_n^{H/L*}) > 0$ in the equilibrium must maximize the UEs' expected payoff, i.e., $\hat{e}_n^{H/L*} \in \arg \max_e \{\beta(\theta_H|\hat{e}_n^H)r_H + \beta(\theta_L|\hat{e}_n^L)r_L - \theta_{H/L}\hat{e}_n^{H/L}\}$
- 2) The gNB's posterior beliefs conditional on equilibrium amounts of sensing data must satisfy the Bayes' rule:

$$\beta(\theta_{H/L}|\hat{e}_n^{H/L}) = \frac{P_{H/L}(\hat{e}_n^{H/L})\beta_{H/L}}{\sum_{\{H,L\}}\beta_{H/L}P_{H/L}(\hat{e}_n^{H/L})}$$

with $P_{H/L}(\hat{e}_n^{H/L}) > 0$ for at least one type of UEs.

- 3) The posterior beliefs are not restricted, i.e., if $P_{H/L}(\hat{e}_n^{H/L}) = 0 \Rightarrow \sum_{\{H,L\}}\beta_{H/L}P_{H/L}(\hat{e}_n^{H/L}) = 0$, then, the $\beta_{H/L}(\theta_{H/L}|\hat{e}_n^{H/L})$ can take any value in $[0, 1]$.
- 4) The gNB provides rewards to the UEs $W = \beta(\theta_H|\hat{e}_n^H)r_H + \beta(\theta_L|\hat{e}_n^L)r_L$.

In this research work, we focus on the separating PBE, among the multiple PBEs that the game between the gNB and each UE may have. In the separating PBE, the UEs provide "signals" to the gNB regarding their potential to provide sensing data that identify each UE's type, i.e., H or L, exactly.

Definition 2: (Separating PBE) A separating equilibrium is a PBE where each type of UE chooses a different "signal" in equilibrium $e_n^{H*} \neq e_n^{L*}$ so that $\beta(\theta_H|e_n^{H*}) = 1$, $\beta(\theta_L|e_n^{L*}) = 1$, $w_{H/L} = r_{H/L}$. The corresponding amounts of reported sensing data are: $S = \{(e_n^{H*}, e_n^{L*}) | e_n^{L*} = 0 \text{ and } e_n^{H*} \in [\frac{r_H - r_L}{\theta_L}, \frac{r_H - r_L}{\theta_H}]\}$.

Based on the condition of incentive compatibility, where each UE is encouraged to choose a strategy that matches their type, i.e., H or L, we have: $r_H - \theta_L e_n^{H*} \leq r_L \Leftrightarrow \frac{r_H - r_L}{\theta_L} \leq e_n^{H*}$ and $r_H - \theta_H e_n^{H*} \geq r_L \Leftrightarrow \frac{r_H - r_L}{\theta_H} \geq e_n^{H*}$. According to the Cho-Kreps intuitive criterion [13], a unique pure-strategy equilibrium is given by the "least-cost" separating PBE (SPBE), which is denoted as SPBE: $[e_n^{L*} = 0, e_n^{H*} = \frac{r_H - r_L}{\theta_L}]$. Thus, each UE's amount of sensing data reported to the gNB is: $\hat{e}_n^L = e_n^L + e_n^{L*}$ or $\hat{e}_n^H = e_n^H + e_n^{H*}$.

III. GENESIS: GREEN ENERGY EFFICIENCY OPTIMIZATION IN ISAC

In this section, we focus on the resource management operation of the GENESIS framework, while incorporating the proposed incentivization mechanism. Section III-A presents the ISAC sensing and communication model, while Section III-B formulates the UE energy efficiency optimization problem and outlines the game-theoretic solution for optimizing the transmission power and power splitting between the sensing and communication operations.

A. ISAC Modeling

1) *Sensing*: To sense data from a target, each UE n radiates an Orthogonal Frequency Division Multiplexing (OFDM) waveform, which is reflected back conveying the detected information. The radiated signal by UE n at time t :

$$s_n(t) = e^{j2\pi f_c t} \sum_{l=0}^{S-1} g_n c_n^l e^{j2\pi W_{ISAC}(t-lT_s)} \times \text{rect}\left[\frac{t-lT_s}{T_s}\right] \quad (1)$$

where S is the number of consecutive integrated symbols radiated towards the target, T_s [s] is the duration of a completed OFDM symbol, f_c [Hz] is the center frequency of the wireless channel, g_n is the amplitude of the integrated waveform, c_n^l is the phase code of the modulated symbol, and $\text{rect}[z]$ is a pulse function, giving 1 when $0 \leq z \leq 1$ and 0 otherwise.

The reflected signal by the target to node n is written as:

$$z_n(t) = \int_{-\infty}^{\infty} q_n(\tau) s_n(t - \tau) d\tau + w(t) \quad (2)$$

where $q_n(t)$ and $w(t)$ denote the impulse response and zero-mean Additive White Gaussian Noise (AWGN), respectively.

The performance of each UE's n sensing operation is evaluated by calculating the Mutual Information (MI) between the reflected signal $z_n(t)$ and the impulse response $q_n(t)$ conditioned on the initial waveform $s_n(t)$:

$$\begin{aligned} MI_n(x_n, P_n) &= I(z_n(t), q_n(t) | s_n(t)) \\ &= \frac{1}{2} ST_s W_{ISAC} \log_2(1 + \gamma_{n,sens}^{ISAC}) \end{aligned} \quad (3)$$

with signal-to-noise-ratio (SNR) for sensing $\gamma_{n,sens}^{ISAC} = \frac{x_n P_n ST_s^2 |Q_n(f)|^2}{I_0}$, considering an orthogonal frequency-division multiple access or OFDMA-based sensing data exchange where $Q_n(f)$ is the Fourier transform of the impulse response $q_n(t)$ and I_0 is the power of zero-mean AWGN. Also, P_n denotes the UE's uplink transmission power and $x_n \in [0, 1]$ is the power splitting factor, where $x_n P_n$ and

$(1 - x_n)P_n$ transmission power is used to support the sensing and communication operation, respectively.

UE n reports the sensing data $\hat{e}_n^{H/L}$, $\forall \in \mathcal{N}_H \cup \mathcal{N}_L = \mathcal{N}$ to the gNB adopting the NOMA technique and considering that the Successive Interference Cancellation (SIC) technique is implemented at the gNB, and considering without loss of generality that the UEs channel gains are sorted as $G_1 \leq \dots \leq G_n \leq \dots \leq G_N$. Thus, each UE's n throughput to report the sensing data $\hat{e}_n^{H/L}$ to the gNB is given as follows,

$$R_n^{ISAC}(\mathbf{x}, \mathbf{P}) = W_{ISAC} \log_2\left(1 + \frac{x_n P_n G_n}{I_0 + \sum_{n'=1}^{n-1} G_{n'} x_{n'} P_{n'}}\right) \quad (4)$$

where W_{ISAC} [Hz] denotes the bandwidth allocated by the gNB for the sensing operation.

2) *Communication*: The UE n 's throughput in order to report its communication-related data to the gNB is:

$$R_n^{COM}(\mathbf{x}, \mathbf{P}) = W_{COM} \log_2\left(1 + \frac{(1 - x_n) P_n G_n}{I_0 + \sum_{n'=1}^{n-1} G_{n'} (1 - x_{n'}) P_{n'}}\right) \quad (5)$$

where W_{COM} [Hz] denotes the bandwidth allocated by the gNB for the communication operation.

Based on Eq. 3 – 5, we formulate the UE's overall utility:

$$U_n(\mathbf{x}, \mathbf{P}) = \frac{w_1 MI_n(x_n, P_n) + w_2 R_n^{ISAC}(\mathbf{x}, \mathbf{P}) + w_3 R_n^{COM}(\mathbf{x}, \mathbf{P})}{P_n + P_c} \quad (6)$$

where $w_1, w_2, w_3 \in \mathbb{R}^+$ denote the weights each UE considers for its sensing and communication operation, and P_c [W] denotes the circuit power.

B. Problem Formulation and Solution

The goal of the GENESIS framework is to enable each UE to determine its optimal uplink transmission power level and its optimal power splitting between the sensing and communication operations in order to maximize its overall experienced energy efficiency (Eq. 6). Thus, the corresponding optimization problem is defined as follows:

$$\max_{\{x_n, P_n\}} U_n(\mathbf{x}, \mathbf{P}) \quad (7a)$$

$$\text{s.t. } P_n^{Min} \leq P_n \leq P_n^{Max} \quad (7b)$$

$$0 \leq x_n \leq 1 \quad (7c)$$

where (7b) and (7c) capture the feasibility constraints of the UE's transmission power and power splitting, respectively.

Given the distributed nature of the optimization problem (7a) – (7c), we formulate it as a non-cooperative game $G = [\mathcal{N}, \{\mathcal{X}_n, \mathcal{P}_n\}_{\forall n \in \mathcal{N}}, \{U_n\}_{\forall n \in \mathcal{N}}]$ among the UEs, where $\mathcal{N}$ denotes the set of UEs, $\{\mathcal{X}_n, \mathcal{P}_n\}$ denotes their strategy space with respect to the power splitting and uplink transmission power, and U_n denotes their payoff function (Eq. 6).

Theorem 1: The non-cooperative game G is a concave n -person game.

Proof: To show that G is an n -person concave game, we need to prove that (i) The strategy spaces are convex

$$\frac{\partial^2 U_n}{\partial x_n^2} = \frac{1}{(P_n + P_c) \ln(2)} \left[-\frac{w_1 S^3 T_s^5 W_{ISAC} |Q_n(f)|^4 P_n^2}{2(I_0 + x_n P_n S T_s^2 |Q_n(f)|^2)^2} - \frac{w_2 W_{ISAC} G_n^2 P_n^2}{(\Gamma + G_n x_n P_n)^2} - \frac{w_3 W_{COM} G_n^2 P_n^2}{(\Delta + G_n(1-x_n)P_n)^2} \right] < 0 \quad (8)$$

$$\frac{\partial^2 U_n}{\partial x_n \partial p_n} = \frac{\partial^2 U_n}{\partial p_n \partial x_n} = \frac{w_1 W_{ISAC} S^2 T_s^3 |Q_n(f)|^2}{2 \ln 2 (P_n + P_c) (I_0 + x_n P_n S T_s^2 |Q_n(f)|^2)} \left[\frac{I_0}{(I_0 + x_n P_n S T_s^2 |Q_n(f)|^2)} - \frac{P_n}{(P_n + P_c)} \right] + \frac{w_2 W_{ISAC} G_n}{\ln 2 (P_n + P_c) (\Gamma + G_n x_n P_n)} \left[\frac{\Gamma}{(\Gamma + G_n x_n P_n)} - \frac{P_n}{P_n + P_c} \right] - \frac{w_3 W_{COM} G_n}{\ln 2 (P_n + P_c) (\Delta + G_n(1-x_n)P_n)} \left[\frac{\Delta}{(\Delta + G_n(1-x_n)P_n)} - \frac{P_n}{P_n + P_c} \right] \quad (9)$$

$$\frac{\partial^2 U_n}{\partial x_n \partial p_{n'}} = \frac{\partial^2 U_n}{\partial p_{n'} \partial x_n} = \frac{G_{n'}}{(P_n + P_c) \ln 2} \cdot \left\{ w_2 W_{ISAC} G_n x_n P_n \cdot \frac{2G_{n'} x_n' P_{n'} \Gamma - \Gamma^2 - \Gamma G_n x_n P_n + G_{n'} x_n' P_{n'} G_n x_n P_n}{(\Gamma + G_n x_n P_n)^2 \Gamma^2} \right. \\ \left. + w_3 W_{COM} G_n (1-x_n) P_n \cdot \frac{-2G_{n'} (1-x_n') P_{n'} \Delta + \Delta^2 + G_n (1-x_n) P_n \Delta - G_{n'} (1-x_n') P_{n'} G_n (1-x_n) P_n}{(\Delta + G_n (1-x_n) P_n)^2 \Delta^2} \right\} \quad (10)$$

and compact sets, which is true given that $\mathcal{X}_n = [0, 1]$ and $\mathcal{P}_n = [0, P_{max}]$; (ii) $U_n(\mathbf{x}, \mathbf{P})$ is continuous in $(\mathbf{x}, \mathbf{P})$, which is true by definition (Eq. 6); and (iii) $U_n(\mathbf{x}, \mathbf{P})$ is a concave function with respect to (x_n, P_n) [14], [15]. In order to prove the latter condition, we need to show that the Hessian matrix of U_n is negative definite, i.e., $\frac{\partial^2 U_n}{\partial x_n^2} < 0$, $\frac{\partial^2 U_n}{\partial p_n^2} < 0$, and

$$\frac{\partial^2 U_n}{\partial x_n \partial p_n} = \frac{\partial^2 U_n}{\partial p_n \partial x_n}. \text{ We set } \Gamma = I_0 + \sum_{n'=1}^{n-1} G_{n'} x_{n'} P_{n'} \text{ and}$$

$$\Delta = I_0 + \sum_{n'=1}^{n-1} G_{n'} (1-x_{n'}) P_{n'}. \text{ Based on Eq. 8, we have}$$

$$\frac{\partial^2 U_n}{\partial x_n^2} < 0. \text{ Then, we study the } \frac{\partial^2 U_n}{\partial p_n^2}. \text{ Let } \hat{U}_n = U_n \cdot (P_n + P_c), \\ A = \frac{\partial \hat{U}_n}{\partial p_n} > 0, \text{ and } B = \frac{\partial^2 \hat{U}_n}{\partial p_n^2} < 0. \text{ Thus, we have } \frac{\partial^2 U_n}{\partial p_n^2} = \frac{(P_n + P_c)^3 B - 2(P_n + P_c)[(P_n + P_c)A - \hat{U}_n]}{(P_n + P_c)^4} \text{ which we need to prove is}$$

negative. For this to happen, the following condition needs to be proved: $(P_n + P_c)A - \hat{U}_n > 0$. We set $\alpha = \frac{x_n S T_s^2 |Q_n(f)|^2}{I_0}$,

$\beta = \frac{x_n G_n}{\Gamma}$, and $\gamma = \frac{(1-x_n)G_n}{\Delta}$, thus, we need to show that $\frac{\alpha(P_n + P_c)}{\alpha P_n + 1} > \log_2(\alpha P_n + 1)$, $\frac{\beta(P_n + P_c)}{\beta P_n + 1} > \log_2(\beta P_n + 1)$, and $\frac{\gamma(P_n + P_c)}{\gamma P_n + 1} > \log_2(\gamma P_n + 1)$ simultaneously hold true. The latter statement holds true given that the circuit power takes very small values and the UEs with good channel conditions transmit at lower power levels compared to users with worse channel conditions. Thus, $\frac{\partial^2 U_n}{\partial p_n^2} < 0$ holds true. Also, we have

$\frac{\partial^2 U_n}{\partial x_n \partial p_n} = \frac{\partial^2 U_n}{\partial p_n \partial x_n}$ based on Eq. 9. Thus, the non-cooperative game G is a concave n -person game. ■

Theorem 2: A Pure Nash Equilibrium (PNE) exists for the non-cooperative game G .

Proof: Given that the non-cooperative game G is a concave n -person game, then based on Theorem 1 in [16], there exists at least one PNE. ■

Until now, Theorems 1 and 2 have established the existence of a PNE in the game G . However, our objective is to not only establish the existence but also the uniqueness of the PNE. To achieve this, we introduce the following weighted non-negative sum of the utility functions $U_n(\mathbf{x}, \mathbf{P})$: $\sigma(\mathbf{x}, \mathbf{P}, \mathbf{r}) = \sum_{n=1}^N r_n U_n(\mathbf{x}, \mathbf{P})$, with $r_n \geq 0, \forall n \in \mathcal{N}$.

Theorem 3: The function $\sigma(\mathbf{x}, \mathbf{P}, \mathbf{r})$ is diagonally strictly concave for $(\mathbf{x}, \mathbf{P}) \in \mathbb{R}^2$ and some $\mathbf{r} > \mathbf{0}$ if: (i) $U_n(\mathbf{x}, \mathbf{P})$ is a strictly concave function of (x_n, P_n) ; (ii) $U_n(\mathbf{x}, \mathbf{P})$ is convex in $[(x_1, P_1), \dots, (x_{n-1}, P_{n-1}), (x_{n+1}, P_{n+1}), \dots, (x_N, P_N)]$; and (iii) There is some $\mathbf{r} > \mathbf{0}$ such that $\sigma(\mathbf{x}, \mathbf{P}, \mathbf{r})$ is concave

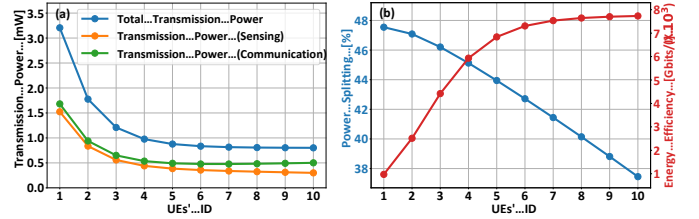


Fig. 1: UEs' transmission power, power splitting, and energy efficiency.

in $(\mathbf{x}, \mathbf{P})$ [17].

Proof: The first condition holds true based on Theorem 1. In order to prove the second condition, we need to show that $\frac{\partial^2 U_n}{\partial x_n^2} < 0$, $\frac{\partial^2 U_n}{\partial p_n^2} < 0$, and $\frac{\partial^2 U_n}{\partial x_n \partial p_n} = \frac{\partial^2 U_n}{\partial p_n \partial x_n}$. We have: $\frac{\partial^2 U_n}{\partial x_n^2} = \frac{G_n P_n G_{n'}^2 P_{n'}^2}{(P_n + P_c) \ln 2} \left[\frac{w_2 W_{ISAC} x_n [2\Gamma + G_n x_n P_n]}{(\Gamma + G_n x_n P_n)^2 \Gamma^2} + \frac{w_3 W_{COM} (1-x_n) [2\Delta + G_n (1-x_n) P_n]}{(\Delta + G_n (1-x_n) P_n)^2 \Delta^2} \right] > 0$ and $\frac{\partial^2 U_n}{\partial p_n^2} = \frac{G_n^2 G_{n'} P_n}{(P_n + P_c) \ln 2} \left[\frac{w_2 W_{ISAC} x_n^2 (2\Gamma + G_n x_n P_n)}{(\Gamma + G_n x_n P_n)^2 \Gamma^2} + \frac{w_3 W_{COM} (1-x_n)^2 (2\Delta + G_n (1-x_n) P_n)}{(\Delta + G_n (1-x_n) P_n)^2 \Delta^2} \right] > 0$, and $\frac{\partial^2 U_n}{\partial x_n \partial p_n} = \frac{\partial^2 U_n}{\partial p_n \partial x_n}$ holds true based on Eq. 10. Similarly, by appropriately choosing $\mathbf{r} > \mathbf{0}$, we derive that $\sigma(\mathbf{x}, \mathbf{P}, \mathbf{r})$ is concave in $(\mathbf{x}, \mathbf{P})$. ■

Theorem 4: The PNE $(\mathbf{x}^*, \mathbf{P}^*)$ is unique.

Proof: Given that the function $\sigma(\mathbf{x}, \mathbf{P}, \mathbf{r})$ is diagonally strictly concave for some $\mathbf{r} = \mathbf{r} > \mathbf{0}$, it is shown based on Theorem 2 [16] that the PNE is unique [18]. ■

IV. NUMERICAL RESULTS

In this section, we have performed a detailed modeling and simulation analysis of the proposed GENESIS framework. We initiate the assessment by evaluating the pure performance of the GENESIS framework (Section IV-A), followed by a scalability analysis in order to demonstrate its efficiency and robustness in large-scale setups (Section IV-B). Then, a comparative evaluation is performed to demonstrate the benefits of the GENESIS framework against the existing state-of-the-art approach of data rate optimization (Section IV-C). It is noted that, unless explicitly specified, we consistently consider the following set of simulation environment parameters in our evaluation: $N = 10$, $S = 10$, $T_s = 5 \mu s$, $|Q_n(f)| = 1$, $I_0 = W \cdot N_0$, with $W = \{W_{ISAC}, W_{COM}\} = 5.25 \text{ GHz}$, $N_0 = -174 \text{ dBm/Hz}$ [19], $\mathbf{w}_1 = [51, 50, 49, 48, 47, 46, 44, 43, 42, 40] \cdot 10^{-3}$, $\mathbf{w}_2 = [46, 45, 44, 43, 42, 41, 40, 39, 37, 36] \cdot 10^{-2}$, $\mathbf{w}_3 =$

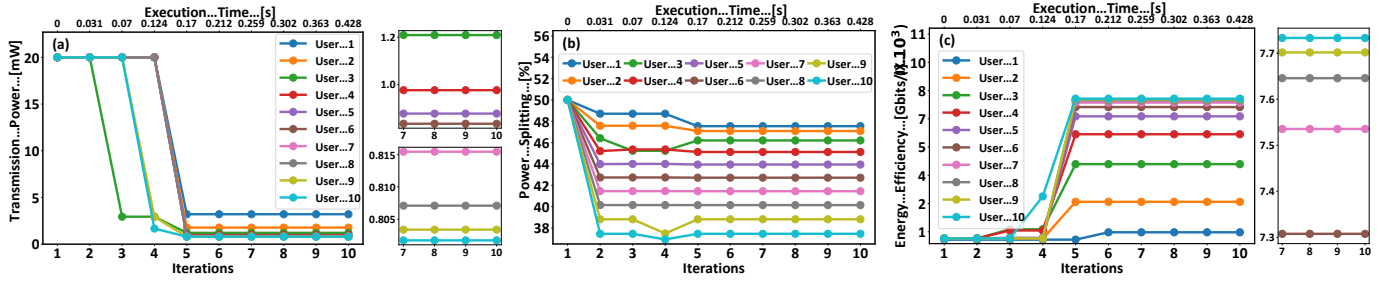


Fig. 2: Convergence characteristics of the GENESIS framework to the unique Pure Nash Equilibrium.

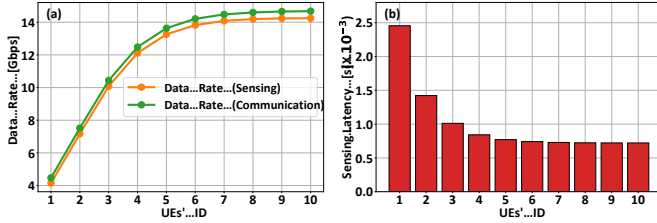


Fig. 3: UEs' data rate and sensing latency.

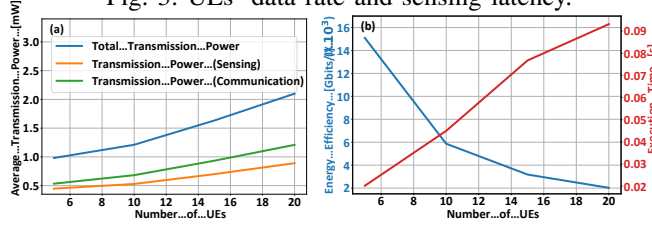


Fig. 4: Scalability analysis.

$[48, 50, 51, 52, 53, 54, 56, 57, 58, 60] \cdot 10^{-2}$, $\mathbf{e} \in [10.1, 10.3] \cdot 10^6$ [bits], $G = [9.99 \cdot 10^{-9}, 6.81 \cdot 10^{-8}, 4.64 \cdot 10^{-7}, 3.16 \cdot 10^{-6}, 2.15 \cdot 10^{-5}, 1.47 \cdot 10^{-4}, 1 \cdot 10^{-3}, 6.8 \cdot 10^{-3}, 4.641 \cdot 10^{-2}, 0.3162]$, $r_H = 100[\frac{\text{C}}{\text{bits}}]$, $r_L = 50[\frac{\text{C}}{\text{bits}}]$, $\theta_L = 70[\frac{\text{C}}{\text{bits}}]$, and $\theta_H = 35[\frac{\text{C}}{\text{bits}}]$. In our considered experiments, all the UEs predominantly prioritize their communication operation over the sensing operation, i.e., $w_3 > w_1 + w_2$, while the UEs with higher ID prioritize even more their communication operation considering a higher communication data volume based on their communication needs. The sensing operation is opportunistic for each UE, aiming at obtaining additional rewards from the gNB. The evaluation was performed on a Dell Tower Desktop with Intel i7 11700K 3.6GHz processor, 32 GB available RAM.

A. Pure Operations and Performance

Fig. 1a presents the UEs' total transmission power, as well as the transmission power used for the sensing and the communication operations, while Fig. 1b shows the power splitting factor x_n and the energy efficiency U_n , as a function of the users' ID. The results reveal that the sensing transmission power is marginally lower compared to the communication power for all the UEs. This preference for prioritizing the communication over the sensing operation arises from the UEs' focus on the former ensuring their communication benefits, with the sensing operation being carried out opportunistically to gain additional rewards from the gNB by following the Spence's model (Section II). Also, the UEs

with higher ID, i.e., having better channel gain conditions in the considered experiment, are characterized by lower total uplink transmission power levels, which is in turn reflected to lower power levels for both their sensing and communication operations. Given that the UEs transmission power decreases as their channel gain conditions improve (i.e., higher UEs' ID), their corresponding achieved energy efficiency levels follow an increasing trend (Fig. 1b).

Fig. 2a – 2c demonstrate the UEs' total transmission power, their power splitting, and their achieved energy efficiency as a function of the GENESIS framework's iterations to converge to unique PNE. The results show that the GENESIS framework operation convergence for all the UEs is achieved in less than 10 iterations, which corresponds to less than 0.5sec. Also, similar to the results presented in Fig. 1, we observe that the UEs of higher ID, i.e., characterized by better channel gain conditions, transmit at lower power levels (Fig. 2a), resulting in higher energy efficiency (Fig. 2c), while exploiting a lower power splitting among the sensing and the communication operations (Fig. 2b). The latter observation holds true, as in the considered experiment, the UEs with higher ID demonstrate an amplified preference for prioritizing their communication operation, primarily attributable to their elevated communication data volume requirements.

Fig. 3a and Fig. 3b shift the focus towards examining the data rates associated with the sensing and communication aspects of the GENESIS framework, as well as the experienced latency in order to report the sensing data to the gNB, respectively. The results reveal that the data rate for communication (Eq. 5) is higher than the corresponding data rate achieved to report the sensing data (Eq. 4), as the UEs invest more effort into the communication operation versus the sensing operation. We also observe that both the communication and sensing data rate increase as well, as the UEs' ID increases. Furthermore, Fig. 3b demonstrates the operation of Spence's model at the separating Perfect Bayesian Equilibrium. In particular, Fig. 3b shows the sensing latency as a function of the UE's ID. It is noted that the higher the UE's ID the higher the amount of collected data, but also the higher is the sensing data rate, as observed in Fig. 3a. Thus, we observe the decreasing trend of the sensing latency for higher UEs' ID demonstrating that the UEs with strong channel gain can efficiently support both the sensing (Fig. 3b) operation via experiencing low sensing latency and the communication operation (Fig. 3a) by achieving high communication data rate.

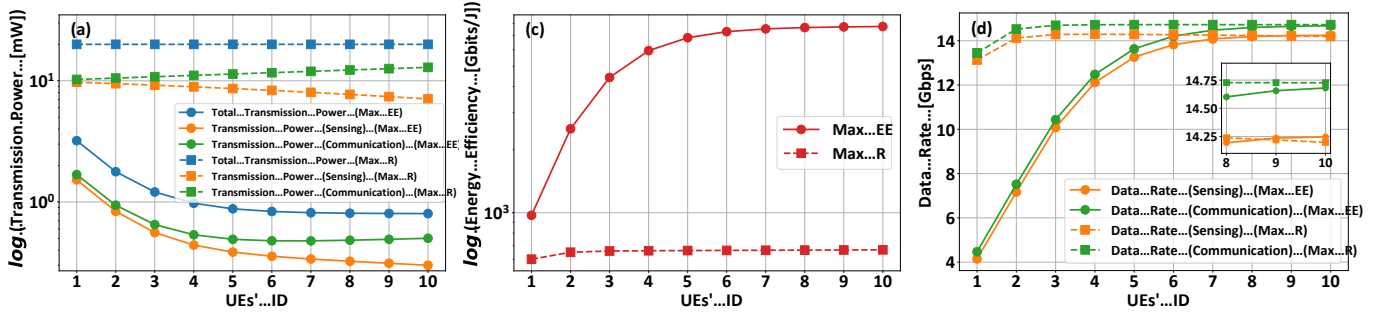


Fig. 5: Comparative evaluation.

B. Scalability Analysis

In this section, we conducted a thorough scalability analysis in order to demonstrate the efficiency and robustness of the proposed model and framework. Fig. 4a and Fig. 4b present the UEs' average transmission power, energy efficiency, and the execution time of the GENESIS framework, as a function of the number of UEs. The results reveal that a 4-fold increase in the number of UEs results in 1.2-fold increase in the UEs' average transmission power levels (with reference to the total power as well as to the powers invested in the sensing and communication operations (Fig. 4a). The execution time of the GENESIS framework exhibits a direct correlation with the growing number of UEs, while the increasing number of UEs has a nearly twofold impact on the achieved energy efficiency due to the increasing interference in the system that impacts both the sensing and communication operations.

C. Comparative Results

In this section, the GENESIS framework is compared against a pure data rate optimization (Max R) framework aiming at determining the optimal uplink transmission power and power splitting for each UE. Fig. 5a – 5c illustrate the uplink transmission power, energy efficiency, and data rate for both comparative scenarios. The results reveal that even if the data rate optimization framework achieves higher data rate levels for both the sensing and the communication operations (Fig. 5c), it sacrifices a significant amount of transmission power (Fig. 5a), resulting in substantially lower achieved energy efficiency (Fig. 5b).

V. CONCLUSION

In this paper, a novel ISAC network operation is presented that employs incentives, following Spence's model under Contract Theory, to encourage UEs to sense, collect, and report their data. The GENESIS framework combines this incentivization mechanism with optimal resource management, allowing the UEs to maximize their energy efficiency. The corresponding resource management problem is formulated as a non-cooperative game, and a Pure Nash Equilibrium is proven to exist. Numerical results demonstrate not only the GENESIS' energy-efficiency and fast convergence, but also the fact that outperforms existing data rate optimization approaches in ISAC networks.

REFERENCES

- [1] F. Liu, Y. Cui, C. Masouros, J. Xu, T. X. Han, Y. C. Eldar, and S. Buzzi, "Integrated sensing and communications: Toward dual-functional wireless networks for 6g and beyond," *IEEE Journal on Selected Areas in Communications*, vol. 40, no. 6, pp. 1728–1767, 2022.
- [2] J. An, H. Li, D. W. K. Ng, and C. Yuen, "Fundamental detection probability vs. achievable rate tradeoff in integrated sensing and communication systems," *IEEE Trans. on Wireless Comm.*, pp. 1–1, 2023.
- [3] Z. Behdad, T. Demir, K. W. Sung, E. Björnson, and C. Cavar, "Power allocation for joint communication and sensing in cell-free massive mimo," in *IEEE GLOBECOM*, 2022, pp. 4081–4086.
- [4] H. Hua, T. X. Han, and J. Xu, "Mimo integrated sensing and communication: Crb-rate tradeoff," *IEEE Trans. on Wir. Comm.*, pp. 1–1, 2023.
- [5] M. Liu, M. Yang, H. Li, K. Zeng, Z. Zhang, A. Nallanathan, G. Wang, and L. Hanzo, "Performance analysis and power allocation for cooperative isac networks," *IEEE Internet of Things Journal*, vol. 10, no. 7, pp. 6336–6351, 2023.
- [6] Z. Lyu, G. Zhu, and J. Xu, "Joint trajectory and beamforming design for uav-enabled integrated sensing and communication," in *IEEE ICC*, 2022, pp. 1593–1598.
- [7] M. B. Janjua, E. Memişoğlu, K. A. Qaraqe, and H. Arslan, "Secure pilot allocation for integrated sensing and communication," in *IEEE Globecom Workshops (GC Wkshps)*, 2022, pp. 1466–1471.
- [8] F. Dong, F. Liu, Y. Cui, W. Wang, K. Han, and Z. Wang, "Sensing as a service in 6g perceptive networks: A unified framework for isac resource allocation," *IEEE Transactions on Wireless Communications*, vol. 22, no. 5, pp. 3522–3536, 2023.
- [9] J. Zhu, Y. Cui, J. Mu, L. Hu, and X. Jing, "Power minimization strategy based subcarrier allocation and power assignment for integrated sensing and communication," in *2023 IEEE Wireless Communications and Networking Conference (WCNC)*, 2023, pp. 1–6.
- [10] F. Dong and F. Liu, "Localization as a service in perceptive networks: An isac resource allocation framework," in *IEEE Int. Conf. on Communications Workshops (ICC Workshops)*, 2022, pp. 848–853.
- [11] Y. Zhuo and Z. Wang, "Performance analysis of isac system under correlated communication-sensing channel," *IEEE Transactions on Vehicular Technology*, pp. 1–6, 2023.
- [12] J. Zuo and Y. Liu, "Reconfigurable intelligent surface assisted noma empowered integrated sensing and communication," in *2022 IEEE Globecom Workshops (GC Wkshps)*, 2022, pp. 1028–1033.
- [13] P. Bolton and M. Dewatripont, *Contract theory*. MIT press, 2004.
- [14] M. Diamanti, P. Charatsaris, E. E. Tsiropoulou, and S. Papavassiliou, "The prospect of reconfigurable intelligent surfaces in integrated access and backhaul networks," *IEEE Transactions on Green Communications and Networking*, vol. 6, no. 2, pp. 859–872, 2022.
- [15] —, "Incentive mechanism and resource allocation for edge-fog networks driven by multi-dimensional contract and game theories," *IEEE Open Journal of the Communications Society*, vol. 3, pp. 435–452, 2022.
- [16] J. B. Rosen, "Existence and uniqueness of equilibrium points for concave n-person games," *Econometrica: Journal of the Econometric Society*, pp. 520–534, 1965.
- [17] J. C. Goodman, "Note on existence and uniqueness of equilibrium points for concave n-person games," *Econometrica*, vol. 48, pp. 251–251, 1965.
- [18] G. Fragkos, N. Kemp, E. E. Tsiropoulou, and S. Papavassiliou, "Artificial intelligence empowered uavs data offloading in mobile edge computing," in *IEEE International Conference on Communications*, 2020, pp. 1–7.
- [19] L. Zhao, D. Wu, L. Zhou, and Y. Qian, "Radio resource allocation for integrated sensing, communication, and computation networks," *IEEE Trans. on Wireless Comm.*, vol. 21, no. 10, pp. 8675–8687, 2022.