Project Description – Science and Technology Center for Sustainable and Trustworthy Connectivity (STC^2)

A. STC^2 Rationale

Motivation The drive to connect everyone and everything has fueled generations of technologies that have shaped our civilization. The undeniable fact is that we cannot think of any societal activity that does not involve some form of digital connectivity anymore. This connected digital era, where a significant percentage of information flows through personal devices, however, comes with unintended consequences. First, we are increasingly seeing the significant projected impact on depleting energy reserves, due to the deluge of information generated, computed, transmitted and consumed. This impact is quickly multiplying and is expected to have unprecedented growth fueled by the advent of AI and its ever-growing required energy. Second, we are increasingly seeing the additional negative impact on the environment of used electronics of personal and computing devices, i.e., electronic-waste (e-waste) is one of the fastest growing solid waste streams in the world [1]. Third, and an equally important consequence is a *societal* one. The redundant, exploitive, and fictitious content, i.e., digital-waste (d-waste) impedes efficient decision making. Importantly, with social media as the primary source of information for a significant percentage of society, the very connection that enables more free information flow also enables disinformation and misinformation flow with serious consequences.

These unintended consequences are mainly due a siloed design philosophy to building this technology that has long outpaced the foundational research that should have preceded it. In particular, the digital revolution driven by the Internet, the wireless revolution leading to today's newest applications, and the data revolution that has brought us cloud computing and future AI have all proceeded with quickly escalating societal penetration and litt to no societal impact evaluation. *The complex interaction of technology, humans, and the environment must be understood at a foundational level, using scientific principles, in order for humanity to advance while ensuring no-harm.*

Intellectual merit We propose the *Science and Technology Center for Sustainable and Trustworthy Connectivity* (STC^2) to identify, research, and avert these growing areas of worry. STC^2's research will quantify how *connectivity* both enhances and challenges trustworthiness and sustainability and use this to better design our information representation, processing, machine learning, communication systems, materials, and hardware to lead to a more sustainable future. This integrative vision starts with identifying the correct questions to ask about this future we wish to construct and requires expertise of researchers from a large spectrum of science and technology disciplines: machine learning, communications, information theory, human-machine interaction, cognitive science, law, wireless systems, electromagnetic, signal processing, circuit design, meta-materials, biosensors, and batteries. We will work together to understand how humans and machines process information and redefine communication and computing (AI) towards energy neutrality, and reducing d-waste, and e-waste as central objectives. This interdisciplinary initiative aims to establish a new field: *science of sustainable and trustworthy connectivity*.

Why STC^2? Towards a Unified Theory of Connectivity Across Information, Matter and Energy Our civilization is at the point where physical and cyber worlds are getting increasingly closer. As such, connectivity needs to include all physical and cyber beings, the former of which centers around the communication that is truly content (e.g., meaning) aware, and the latter increasingly emulating human/bio behavior. We thus advocate for the need to unify energy and information in conjunction with the matter that generates, conveys and

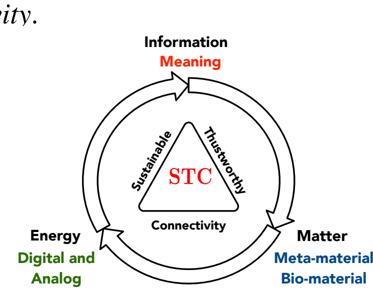

Figure 1: STC^2 Rationale.

processes information – see Fig.1.

The Moment is Opportune for Sustainable and Trustworthy Connectivity (STC) The relentless surge in energy consumption from cellular networks is pushing operators to extreme measures, such as shutting down mid-band 5G radios at night—a stark step to avert an impending energy crisis. Meanwhile, as machine learning algorithms grow ever more powerful and data demands skyrocket, massive data centers now consume as much energy as small cities, straining power grids worldwide. As human consumers of information, while we may make decisions to buy electric vehicles instead of fossil-fuel-based cars, we almost never consider the environmental impact of watching a Netflix movie, or querying ChatGPT. Are these harmless, or does scaling such activities lead to an unsustainable future? These are just a few of the unintended consequences of connectivity – without even accounting for the growing issues of e-waste, spectrum congestion, and the rampant spread of misinformation. With a collaborative multi-university STC^2, our goal is to focus on the wholistic impact our desire for connectivity has on the environment, and how we can better design our information representation, processing (including machine learning), transmission systems, as well as guiding human behaviors and regulations needed for Sustainable and Trustworthy Connectivity (STC), via a comprehensive research agenda that we summarize under four focus areas and directions, see Fig 2. These are:

[Focus 1] Quantifying the Environmental Impacts of Trustworthy Connectivity. To fully grasp the impact of our desire for connectivity on the environment, we will examine factors such as e-waste, radio-frequency noise and exposure, d-waste, energy consumption, and misinformation. We will quantify how connectivity both supports and challenges sustainability.

[Focus 2] Information Representation and Processing for STC. Information is increasingly being generated by machines rather than humans, leading to massive amounts of data to be efficiently represented, condensed, and processed. We tackle this, recognizing that AI will be both beneficial here, and also potentially problematic from a sustainability perspective in terms of the energy needed for manufacturing the hardware and batteries, and training and querying the models.

[Focus 3] Information Transmissions for STC Equipped with a comprehensive understanding and qualification model of connectivity's impact provided in Focus 1, we will work to mitigate these effects by designing innovative transmission techniques and merging traditional performance metrics with sustainability metrics.

[Focus 4] Bridging Human Trust, Information Integrity, and Environmental Responsibility in the Age of Digital Connectivity From incentivizing human behavior and to uncovering the necessary regulations for sustainable and trustworthy connectivity, this focus area will work closely with all foci areas, notably with (i) Focus 2 towards trustworthy information identification and representation (ii) Focus 1 in reduction of misinformation. Together all finding will impact informing and creating science policies that are both forward looking and responsibility driven for a sustainable future.

B. STC^2 Research Plan – Science of Connectivity

1 Quantifying the Environmental Impacts of Trustworthy Connectivity

Various impacts of connectivity have been studied, including the rising energy demands of wireless networks and devices. Providers like AT&T have focused efforts on reducing their $1.6B yearly corporate power bill for running their network [2]. Our center will look not just at transmission costs in a wireless network, but at the whole environmental impact of connectivity. We start by quantifying the impact, setting the stage for which aspects of sustainable connectivity to focus on.

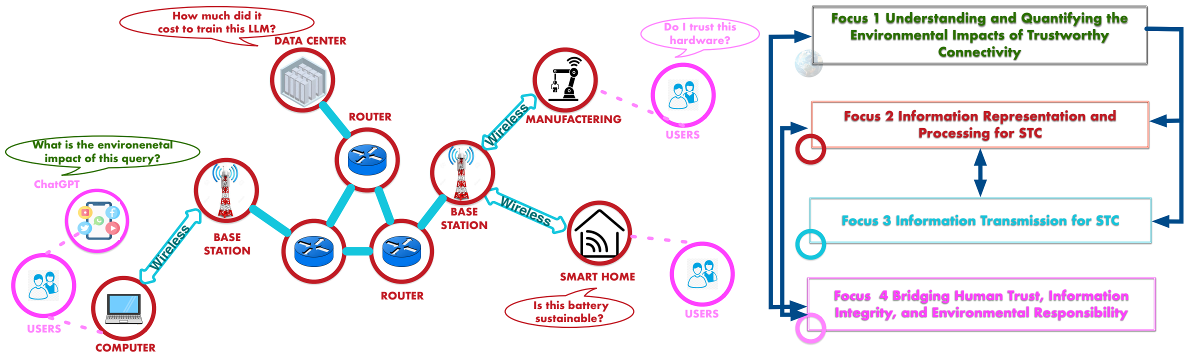

Figure 2: STC^2 Research Plan: The four foci and their interactions are highlighted in color to emphasize their impact on the digital connectivity.

> **Challenge:** How can we minimize the environmental impact of wireless devices?
> **Impact:** We can assess how to best use, reuse, and recycle wireless electronics.

Electronic-waste Perfluoroalkyl and polyfluoroalkyl (PFAS) substances, or *forever chemicals*, are widely used in semiconductors, screens, and plastics for electronic devices. Despite the effort to understand and attempt to mitigate the use of PFAS in semiconductor manufacturing, there is a whole industry around the design of base station, access points, satellite, user equipment, and more than eighteen billion portable devices where PFAS and other toxic chemicals are used regularly. Each year, approximately one billion new devices are produced, many with a lifespan of just two to three years. We will develop metrics to quantify the impact of using and manufacturing PFAS-based connectivity devices.

> **Challenge:** How do we minimize RF noise pollution and decrease human exposure to EM radiation?
> **Impact:** The deleterious effects of the principle contributors can be mitigated.

Radio-frequency noise pollution and exposure to electromagnetic radiation One growing form of pollution is the elevated man-made *noise* across wide spectrum ranges. As wireless demand grows, RF noise from numerous devices increasingly threatens sensitive systems, with incidents like radar altimeter interference and risks to radar astronomy highlighting potential societal impacts. Future RF-sensitive implants and concerns about RF pollution's effects on human health, wildlife, and ecosystems underscore the need for action. We will focus on modeling system and hardware-level characterizations of the pollution. Then, we will produce new techniques for lowering this pollution and new regulators to develop new strategies for RF certification, planning, and deployment (see Focus 4). In terms of EM radiation effects on human health, PIs Love and Hochwald pioneered research on the effect of multiple transmit antennas on EM exposure and waveform designed subject to exposure constraints [3]. Regulatory filings seem to show that average exposure levels per device are actually *increasing*, with devices operated at or near legally allowed limits. We will develop new space-time-frequency signaling techniques to minimize EM exposure while while guaranteeing performance.

> **Challenge:** How do we identify misinformation and disinformation? How can we develop a rigorous way of establishing trustworthiness?
> **Impact:** We can rearchitect networks to minimize misinformation and guarantee some notion of trust.

Digital-waste: redundant, exploitive, and fictitious content In working towards sustainable and trustworthy connectivity, one obvious question is what percentage of data is redundant, fictitious, or exploitative?

This is important not only for sustainability (e.g., transmitting spam is a waste of bandwidth and communication resources), but also for trustworthiness (i.e., we want to trust the content we see). Many aspects of redundant and fictitious content can be traced to human behavior and several factors including anonymity, lack of fact-checking, financial incentives, political manipulation, and advancements in technology: AI-powered tools make it easier to create realistic but false content, such as deepfakes and synthetic voices. We will develop metrics to understand the impact of such content including the 1) the erosion of trust in institutions / media outlets, 2) social division, 3) economic damage, and 4) public health risks.

> **Challenge:** How do we quantify and monitor the energy consumption of connectivity?
> **Impact:** This knowledge can be used to understand and influence human connectivity behavior and enourage energy conservation.

Exponential growth in energy consumption in connectivity and AI The exponential increase in energy consumption of the various cellular generations [4] leads to drastic moves by cellular operators to power-down some of their network at night [2]. Meanwhile, while large language models (as an example of recent AI successes) are extraordinary, so are the energy costs to manufacture the specialized processors, and compute time to train them. Websites [5] and articles have started popping up which aim to quantify the carbon footprint of AI [6]. For both connectivity and AI, our center will work with UIC's Energy Resources Center to quantify and monitor the impact on energy, and develop new metrics for the energy versus gain tradeoffs of these technologies.

Quantifying the environmental cost per bit of transmission One way to quantify the environmental impact of fossil fuels is by measuring tons of carbon dioxide (or equivalent) produced. Similarly, woodland carbon units (WCU) represent carbon removed by planting trees, and toxins in water are measured in parts per trillion, with health-based thresholds. However, there is no standard metric for environmental cost per bit of communication. Such a measure would help people understand the environmental "cost" of a communication session, influenced by the location of source and destination, link speed, and processing requirements – all factors largely invisible to users. Importantly, environmental and monetary costs differ; for example, downloading a movie on an airplane has a different environmental impact than at home, even if priced similarly. Our center will develop useful metrics for quantifying the sustainability cost of querying a learning model, and investigate energy efficient early-exit (early decision) strategies. At the moment, there is essentially no cost to querying say ChatGPT beyond electrical and bandwidth costs – is this a sustainable way forward? Would it be better to place AI nodes closer to user nodes rather than in the centralized system as currently done to save on transmission costs at the possible expense of more hardware? Once such metrics are established, incentive mechanisms for minimizing consumption and recycling can be considered.

2 Information Representation and Processing for STC

Sustainable connectivity centers around connecting information generated at point A with its destination in point B in a way that is mindful of the total "environmental cost" of the entire process, including information representation, storage, and transmission. Trustworthy connectivity centers around trusting the information and information processing used to enable this connectivity. We will develop new theories for information representation and processing tailored to the changing digital world, focusing on sustainability and trustworthiness as alternative to traditional metrics focused purely more and faster connectivity.

> **Challenge:** How do we move beyond oversimplified engineering models for information and, instead, use models that fully characterize models that capture the characteristics of human behavior?
> **Impact:** A novel theory that incorporates meaning and context of information will revolutionize the way networks are developed, analyzed, and deployed.

The Fundamental Theory of Semantic Information In information theory [7], a mathematical field which quantifies the fundamental limits of representation and transmission of information, "all messages are created equal" – that is, the mathematical abstraction of information is content-agnostic. This approach has driven communications network design to date and paved the way to the digital era, mainly due to this separation of information from the meaning of what it represents, enabling simple design insights. In a world where machines are increasingly communicating with humans, and artificial generative intelligence has taken flight, it is difficult to justify an approach that essentially ignores the human element in quantifying information. Semantic communications is the novel paradigm that tackles the challenge of mathematically abstracting meaning. Still emerging, and pioneered by PI Yener [8], semantic communications aims to convey the intended meaning of messages from a transmitter to a receiver, thus diverging from the earlier paradigm of exactly replicating messages represented by digital sequences sent from a transmitter at the receiver. Instead, messages interpreted as similar in meaning are deemed *sufficiently useful* at the receiver side, in effect reducing the number of retransmissions needed. Such a framework pairs well with modern AI tools, in efficient extraction of semantic features, as well as future use cases, where receivers are empowered with decision making in order to complete a prescribed task, such as classifying content as potentially harmful [9]. Our recent results point to promising gains in efficiency when semantic feature extraction is paired with pre-trained models in classification problems [10, 11]. In conjunction with Focus 4, this direction will tackle the construction of the interdisciplinary theory of semantic information and the ensuing communication system design aspects. Important factors that couple well with such an approach are context and situation awareness [12], as well as differences in knowledge bases of communicating parties. In addition, this direction, led by PI Yener, will provide the desgin framework for communicating to accomplish a prescribed (or learned) task, namely goal-oriented networked communication. This will also necessitate to develop new levels of abstractions suitable for AI-driven communication in hyperconnected environments—akin to the OSI model for current communication networks but tailored to machines that continually refine, contextualize, and track purpose and meaning.

Challenge: How can we make AI truly sustainable?
Impact: We will reduce the resources (energy, data, time, bandwidth, hardware) needed for tomorrow's AI applications.

Sustainable Processing with AI/ML AI and ML will be an integral part of industry, science, and information generation and consumption from now on, and while power of large learned models (e.g., LLMs) is awe-inspiring, they require an astronomical amount of data and compute energy. It is time to take a clear look at the cost of such advances obtained in Focus 1, and use these to better shape future ML/AI. Our center will focus not just on mainstream ideas for making AI/ML more efficient like 1) making AI hardware more energy efficient or 2) how to co-design AI hardware and software / algorithms; but we will look at more basic questions such as 3) determining the fundamental limits between AI metrics (e.g., classification accuracy) and the overall energy consumption to achieve it, accounting for both hardware *and* software costs. We will also 4) look at how to train in novel and sustainable manners, not just for training at data centers, but at the end nodes, where it is thought that AI/ML will eventually be deployed[1]. In practical machine learning applications, a model is initially trained to reach a high level of accuracy before deployment – this initial training is often extremely energy demanding. However, nearly every application environment is dynamic, marked by ongoing changes in data distributions. Over time, these shifts make the deployed model less effective, necessitating resource-intensive retraining with large volumes of new and old data. Our team includes Prof. Bing Liu, the world's leading expert on continual learning, who will lead the team in a wholistic investigation of the true energy cost of training and maintaining AI, following his continual

[1]In fact, we hypothesize that it is actually more energy efficient to push AI/ML from the centralized model we have now to as close as we can to the information sources/destinations.

learning paradigm [13, 14]. This paradigm offers a more sustainable solution by enabling the system to detect distribution shifts and adapt to new data incrementally, and applies to the continual pre-training or adaptation of large language models (LLMs) [15, 16].

Challenge: How can we identify and remove digital d-waste?
Impact: We will find ways to identify d-waste, minimize their presence, and rigorize trustworthiness.

Removing the digital-waste for sustainable and trustworthy connectivity Humans and machine produce much for information than we can possibly consume and this will only become more and more of an issue. In working towards sustainable and trustworthy connectivity, we need to look beyond simply compressing information before transmission, but also to reduce the amount of un-necessary information in the first place. Our center will look at reducing digital d-waste in a variety of settings, including 1) sensor networks including bio, earth, satellite, security cameras used to understand and quantify our world, where data will be compressed right at source, and 2) we will develop fundamental tools to detect mis-information (spam information, or information that serves more harm than good). We will explore this challenge through the lens of timeliness, an essential but understudied aspect of misinformation dynamics. Modern dynamic systems often rely on information packets that include timestamps. In such systems, outdated misinformation will eventually be replaced by newer, accurate data as it propagates through the network, making timeliness a key factor in determining the persistence and impact of false information. We identify two key mechanisms by which misinformation can persist in these systems: first, through the continuous generation of misinformation, where data mutates with a certain probability during communication between nodes, consistently creating inaccurate versions of the latest information; and second, through time-stomping, where timestamps or version numbers of misinformation are altered, allowing it to appear fresh and trick nodes into accepting it over newer, accurate packets, prolonging its impact. Doing so not only improves content quality but also reduces computational and communication costs, as misinformation often spreads rapidly. Our team has extensively researched this problem, focusing on detecting fake reviews and misinformation on platfoms like Twitter (X) [17–19] and will target a framework for *detecting misinformation in networks.*

Challenge: How to use / develop sustainable electronics for connectivity, and in particular batteries?
Impact: We can reduce and/or minimize the environmental impact of connectivity-based e-waste.

Sustainable End-user Electronics One cost of connectivity in our digital age are all the PFAS-based electronics needed to support it, from cell phones, to base stations, to backhaul and wired networks, to servers and AI, as will be quantified in Focus 1. Our center will look at materials for alterative and sustainable (biodegrabable, more easily manufactured) information storage and processing, and at developing sustainable batteries. As one example case study: one of the key reasons people replace cell phones is battery life – extending this will lead to longer phone life-spans, reducing the waste generated by phones. Our team includes Prof. Reza Shahbazian-Yassar, a leading expert in sustainable battery technologies who will lead this charge. Concretely, our strategies include (i) enhancing thermal safety, such as using graphene coatings on metal-oxide cathodes, to preventor seeking alternatives to scarce materials. (ii) To further improve energy density and performance, we will explore next-generation Li metal batteries including graphene oxide coatings on separators and developing innovative polymer electrolytes. (iii) To lower CO2 emissions in battery manufacturing, we will integrate techniques like 3D printing of polymer electrolytes. These advances aim to make energy storage solutions more sustainable, efficient, and eco-friendly.

Challenge: How can we manufacture trustworthy electronics needed for connectivity?
Impact: We can establish techniques and criteria for hardware integrity.

Trustworthy Connectivity Electronics Ensuring the authenticity and integrity of electronic devices is essential for secure and trustworthy operation, especially in an era of globalized supply chains involving multiple third-party foundries and vendors. Even minor breaches can result in severe financial, operational, or security repercussions. Without verifiable trust at the hardware layer, the entire system stack remains vulnerable to attacks that compromise data integrity and user privacy. One promising approach to address these challenges is to leverage the intrinsic "quirks" of the semiconductor fabrication process, characterize these statistically, and develop protocols to authenticate the provenance and integrity of electronic devices. This comes at a price, and the team, led by Waleed Khalil, will characterize (trustworthiness, overhead) tradeoffs in manufacturing electronics, focusing specifically on the components needed to ensure connectivity (e.g. processors, modems, routers, digital to analog converters, the RF chain).

3 Information Transmissions for Sustainable and Trustworthy Connectivity

Building on the comprehensive understanding and connectivity impact model provided by Focus 1, we will address these effects by designing innovative transmission techniques and integrating traditional performance metrics with sustainability metrics. Our first approach will focus on multi-functional radio systems to reduce spectrum congestion and power consumption. Then, we will develop a mixed-domain (antenna-analog-digital) design within the transceiver, emphasizing low energy usage, minimal e-waste, and reduced electromagnetic spectrum congestion. AI/ML faces energy-consumption challenges (as studied in Focus 2) but we forsee it also enabling transmission to become more sustainable and trustworthy.

Challenge: How can we reduce the spectrum congestion of wireless systems?
Impact: We can develop new theory and techniques for protecting RF devices and assisting regulators.

Multi-function radio systems The center will unify sensing , jamming, and/or communication, which are similar, yet traditionally separated, wireless systems, in order to facilitate trade-offs among them while reducing spectrum congestion. To date most proposed integrated systems focus on *coexistence – non-overlapped resource allocation or interference avoidance* – not optimal resource (time, frequency and energy) allocation to reduce environmental impacts. We will create a multi-function radio framework based on in-band full-duplex. Full-Duplex (FD) communication – including the PI Smida's work [20] – show that we can effectively cancel self-interference. FD transmission and reception capabilities can be used for communications and for novel radio applications – joint operation can efficiently utilize shared frequency bands, hardware, and waveforms. We will target "joint design and optimization," where sensing, jamming and/or communications functions are jointly designed without being limited by any of their legacy counterparts. These clean-slate future designs could offer the ability to dynamically prioritize the reduction of environmental impact of the different functions, and would not impose limitations from any existing standards.

Challenge: What is the minimum *environmental cost* needed to transmit a unit of information?
Impact: We develop a fundamental theory for optimizing and merging traditional performance metrics with sustainability metrics.

Mixed-Domain Design for Sustainable Wireless Transmission The roles of digital and analog components in radio transmission hardware have witnessed interesting trends in the past few decades. In the 1990s-2000s, the trend was to move from analog to digital processing, because digital computation and storage were enjoying rapid advances in semiconductor technologies. However, as radio networks moved towards higher frequencies and larger bandwidths, analog-to-digital conversion, whose improvements do not follow Moore's law, present a fundamental bottleneck. Traditional low-frequency radios at sub-6GHz that manipulate all signals in digital, while desirable, are not feasible in a STC manner in the mmWave and sub-THz bands. As a result, analog processing took on a bigger role to the point that programmable analog became a key enabler for STC. We will develop Antenna-Analog-Digital Domains co-design (Mixed Domain Designs) - a novel theoretical framework and practical designs for sustainable and trustworthy connectivity. Our goal will be to develop bounds on the performance of multi-function radio systems under the constraint of environmental efficiency – provided by Focus 1. We will demonstrate the power of new theoretical and algorithmic foundations using reconfigurable antennas (e.g., pixel, liquid, and Reflected Intelligent Surface(RIS)) and various testbeds at our partner institutions.

Challenge: Can we use, and trust, AI/ML to reduce the environmental impact of transmission?
Impact: We will develop a novel and interpretable AI-based transmission techniques with dramatic reduction in environmental costs.

AI/ML for Sustainable Transmission Focus 2 looked at streamlining AI *itself*; here we will deploy AI to streamline connectivity. While AI models are being deployed at multiple levels of the traditional OSI communication network stack, the efforts are haphazard. A systematic deployment of AI/ML in networks has not been undertaken and will be wholistically undertaken as one of the main goals on the center. We are motivated to first consider an AI-aided **clean-slate, cross-layer** approach for network communication. We envision strategically and skeptically introducing AI-learned boxes at information sources, network nodes / relays and destinations in the hope of jointly optimizing complex non-linear optimization functions and transmission schemes – it is precisely the fact that AI methods perform remarkably well as optimizers of nasty optimization problems that we will employ them. In addition, AI/ML is also expected to perform well in dynamic environments, as it can be used as a powerful "predictor" that can track important design parameters of communication systems, from predicting basic-level traffic patterns (bandwidth and throughput) to predicting the composition and temporal correlation among traffic of various applications (video, audio, online gaming, VR/AR, sensing and control) to predicting application-layer user needs. By predicting system parameters, one can better design new energy-&-power tradeoffs.
Interpreting AI is becoming increasingly important, but has mainly been applied to traditional ML settings. As we will be using AI to improve connectivity and communications in a variety of settings, and it will be important for domain experts in communications to interpret the learning-based results to both ensure trustworthy communication, and understand the underlying function to achieve energy savings through replacing black boxes with a "simplified" more computationally efficient approach as done in co-PI Devroye's prior work [21]. She will lead this effort.

4 Bridging Human Trust, Information Integrity, and Environmental Responsibility in the Age of Digital Connectivity

AI-enabled connectivity will have profound impacts on human welfare and culture. To support Focus 1, our team will assess, measure, and manage these impacts in the areas of scientific and social trust and policy. The core result of this Focus will be new, theoretically grounded, empirically validated approaches that can capture and model data-information-knowledge [22] on human behaviors and trust, equipping AIs to provide visual guidance of human behaviors towards sustainable choices.

Challenge: How can observers, information content, and policy guide human behavior?
Impact: We will generate results that can directly inform policy making and regulation of AI uses to minimize adverse environmental impacts.

Quantifying the connection between trust and connectivity On one hand, digital connectivity allows us to search for information and connect with others, which could increase trust. On the other hand, it also increases the chance of misinformation and polarization, which can reduce trust. Our team will analyze the reciprocal interaction between humans, AI/digital connectivity, and trust. Specifically, we aim to 1) understand how people trust a partner depending on whether it is a human, a non-AI computer algorithm, or an AI companion; 2) understand how the use of digital connectivity/AI affects people's trust in the information they receive, either online or otherwise; and 3) analyze how its use may change trust more broadly across different aspects of society, culture, and government. For this, we will use a combination of lab-based behavioral tasks [23], self-report questionnaires [24], and computational modeling [25].

Studying how guidance in human-AI ecosystems affect trust at the internet-scale We aim to 1) study the online information uses (such as verbal descriptions and visual imagery) for carbon emissions and increased mining and the relation on trust; 2) investigate how social norm-based messages as prior input to AIs/humans to enhance trust perception and knowledge; and 3) estimate the effect of dynamic vs. static visual imagery and verbal content in energy uses and climate change risk messages on viewers' behaviors to share on social media and their effects on trust.

Relating environmental impact and sustainable practices We will assess, measure, and manage the AI-associated carbon emissions, and the implications of increased mining for metals such as copper and rare earth elements required in AI hardware. We will 1) examine how carbon accounting frameworks and life cycle assessment can help evaluate the overall carbon footprint and broader environmental impact of AI activities; and 2) research consumer-driven strategies that could mitigate AI's ecological footprint. We hypothesize that increased transparency can empower consumers, thus we will explore ways to provide accessible information about the energy and material costs of AI products and services. Specifically, we will study if certifications indicating "green" AI practices, similar to eco-labels in other industries, could help consumers identify and support more sustainable AI technologies. 3) examine the effects of economic incentives, such as taxes on AI-related carbon emissions or material use, that would internalize environmental costs and encourage consumers and developers to prioritize greener alternatives. In addition, we will consider how different regulatory standards and state incentives for green energy, AI use, and data center construction could be altered to limit the environmental impact of increased use of AIs. Our work will lead to a behavior data collection to gain considerable insight into the correlation between policy, information content, and trust. We will construct a thorough understanding of behavior differences and alternative uses of eco-tag, visual imagery, and incentives to guide people's actions.

C. STC^2 Team Description

The center unites a diverse (in gender: 8/20 are women despite the STEM gender gap, and in rank) group of experts from seven schools whose expected contributions are shown in Fig. 3.

1) University of Illinois Chicago (UIC, lead): a downtown Chicago public R1 institution that is simultaneously an MSI, HSI and AANAPISI institution and a major force in empowering social mobility for under-served and first-generation college students. Team members include:

• *Besma Smida (PI, Associate Professor, Electrical and Computer Engineering (ECE))* is the PI. She works on designing spectrum-and-energy efficient wireless communications.

• *Natasha Devroye (co-PI, IEEE Fellow, Richard and Loan Hill Professor, ECE)* works in information theory and machine learning for communications. She is also a co-PI of the HDR-Tripods Phase II "IDEAL" institute which brings together 7 schools and over 75 researchers in the Chicago-land area, hence bringing with her the experience of large interdisciplinary centers.

• *Daniela Tuninetti (IEEE Fellow, Department Head and Professor, ECE)* works on cache-aided secure and private distributed function retrieval.

• *Bing Liu (Distinguished Professor and Peter L. and Deborah K. Wexler Professor of Computing, Computer Science)* is a machine learning expert in lifelong and continual learning.

• *Reza Shahbazian-Yassar (Professor and Robert Uyetani Collegiate Professor, Mechanical and Industrial*

Engineering) studies sustainable materials and long-lasting energy storage solutions.

2) Ohio State University (OSU): A leading public and one of the largest higher education institutions in the nation, with the motto of *education for citizenship*, OSU will bring expertise in AI, Human-AI interaction, Communications, Circuits and Biosensors. The team members are:

• *Aylin Yener (co-PI, IEEE Fellow, AAAS Fellow, Director of IEEE Division IX, Roy and Lois Chope Professor, ECE, CSE and ISE)* has expertise in information theory, wireless communications, semantic communications, distributed learning and optimization, AI-native designs.

• *Jinghua Li (Assistant Professor, Material Science and Engineering)* is an expert in biosensors, and flexible sensors, contributing to developing sustainable biolelectronics.

• *Jian Chen (Associate Professor, Computer Science)* is an expert in human-computer interaction, and visual decision making, critical to future connectivity.

• *Waleed Khalil (Professor, ECE)* works on verifying the integrity and traceability of semiconductor components throughout the supply chain.

3) Purdue University: A public, large-grant university with broad research offerings. The university is a member of the Association of American Universities (AAU) and has a graduate engineering program ranked 6th by the U.S. News & World Report. Team members include:

• *David Love (co-PI, IEEE Fellow, AAAS Fellow, NAI Fellow, Nick Trbovich Professor, ECE)* brings with him exceptional experience in and access to the wireless industry: he has worked with numerous industry partners including Samsung, Nokia, Qualcomm, Motorola, AT&T, Texas Instruments, Raytheon, MIT Lincoln Labs, and Lockheed.

• *Luis Gomez (Assistant Professor, ECE)* works in computational electromagnetism focusing on modeling EM wave propagation through biological media.

• *Chih-Chun Wang (IEEE Fellow, Professor, ECE)* works on network scheduling aspects of low-cost, application-driven, low latency coding and network protocols for cyber physical systems.

4) University of Notre Dame: Notre Dame is a private university in South Bend, Indiana, that has a diverse student body and endeavors to be a force for good with its research.

• *Bertrand Hochwald (co-PI, IEEE Fellow, NAI Fellow, Freimann Professor of Electrical Engineering)* works on the theory and practice of wireline and wireless communication, spectrum estimation, and radio-frequency emissions from wireless devices. He will lead Thrust 1.

• *Nicholas Laneman (IEEE Fellow, Professor, EE)* brings expertise in radio spectrum access and coexistence, technology standards, and regulatory policy. As Director of the $25M Spectrum Innovation Center, he also brings expertise in managing large inter-disciplinary scientific centers.

5) University of Maryland, College Park: The largest University both in the State and Washington metropolitan area with close proximity to federal agencies easing the way for federal partnerships & opportunities.

• *Sennur Ulukus (IEEE Fellow, Distinguished University Professor and ECE Department Chair)* investigates effects of connectivity on timely information dissemination, trustworthy information, and spread of misinformation.

• *Zhambyl Shaikhanov (Assistant Professor)* contributes to the area of metasurfaces by designing and experimentally demonstrating new capabilities in wireless networking, security, and sensing.

6) University of Minnesota, Twin Cities: A prestigious public research university that will bring experts from social science and law:

• *Martina Cardone (Assistant Professor, ECE)* envisions contributing to investigating the use of data censoring mechanisms to enable sustainable connectivity.

• *Iris Donga Vilares (Assistant Professor, Psychology)* combines cognitive science, neuroeconomics, and computational modeling to study how people process information and make decisions under uncertainty. She will help develop theories of how humans interact with ML and one another and how we can change people's behavior to minimize negative environmental impacts.

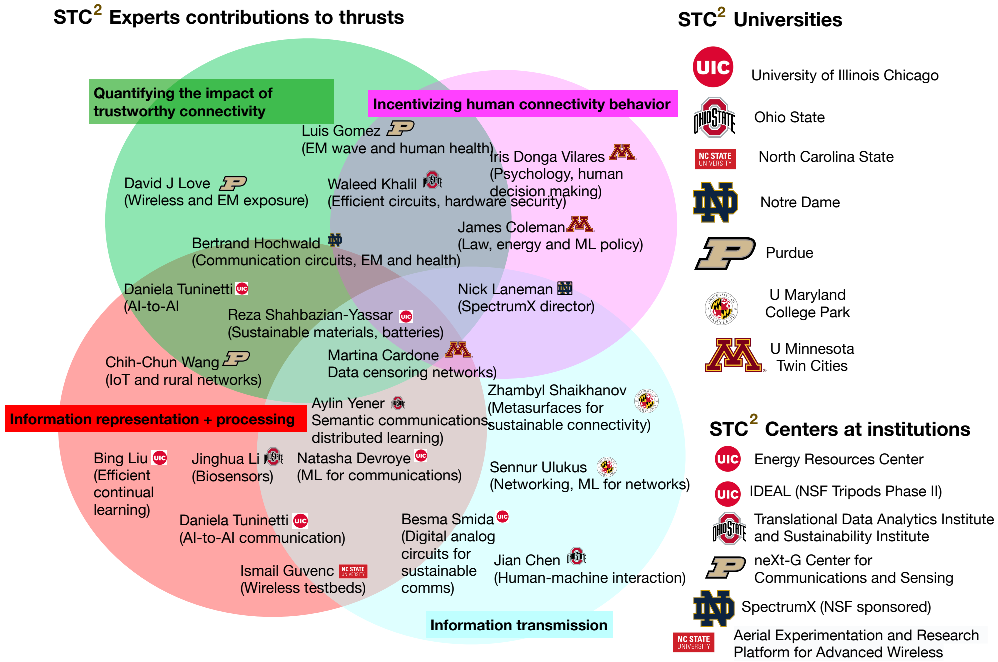

Figure 3: STC^2 team, divided into areas they will contribute to (circles), universities, and expertise.

• *James Coleman (Professor, Law)* is a fellow at the University of Minnesota's Institute on the Environment and the American Enterprise Institute. He specializes in North American energy and infrastructure law and policy. He will explore how the energy system can provide sufficient energy to power an anticipated rise in electricity use for artificial intelligence and do so sustainably.

7) North Carolina State University (NCSU): an RA public university that holds one of the four FCC Innovation Zones in the U.S. which facilitates over-the-air wireless experiments in various frequency bands.

• *Ismail Guvenc (IEEE Fellow, Professor)* is the lead PI for the NSF Aerial Experimentation and Research Platform for Advanced Wireless (AERPAW) platform, and expects to support wireless experimentation of the proposed center ideas through the NSF AERPAW platform.

Proposed Center Organizational Structure The proposed center organizational structure includes a center lead is proposed to be PI Smida, along with communities of Research, Education and Workforce Development, and Collaborative Outreach. Research community will have the four research focus as subgroups and will be coordinated by co-PIs Yener and Devroye. Education and Workforce Development community will be co-lead by Tuninetti and Ulukus both of whom are department chairs at UIC and UMD respectively. Collaborative Outreach community will be co-led by co-PIs Hochwald and Love both of whom have extensive background in collaborating with industry and national laboratories. Overall center operations will be carried our by a managing director (TBN), and external advisory board made up of science, technology and policy experts (TBN) will provide continual feedback to the center.

Broader Impacts

D. STC^2 Integration Strategies

Integration of research: proximity Five of the core partner universities are in Midwest, with UIC, Notre Dame, and Purdue within 2-hr driving distance from each other, and all universities easily reachable to one another. STC^2 will leverage physical proximity by hosting annual workshops, rotating among core partners, to advance the four-focus integrated research agenda (Fig. 2) and to combine the cross-disciplinary strengths of core team members (Fig. 3). Many of our team members already have have a strong record of collaboration, through joint research and professional organizational activities.

Integration of education: graduate, undergraduate and K-12 At the graduate level, we aim to foster center-wide collaboration by competitively funding research assistants co-mentored by faculty from different departments or schools. At both graduate and undergraduate levels, the institutes will explore "sustainable and trustworthy" engineering tracks and encourage undergraduates to join the center's research through REU's. At the K-12 level the center plans to develop modules for Project Lead the Way, which the host institution UIC has been heavily involved in in the past, to create an educational pathway between high schools, community colleges, and the workforce. The center will seek to involve existing educational outreach programs such as for example UIC's Women in Engineering Summer Program, a free, 3-week, non-residential program that offers high school students an unparalleled opportunity to learn more about engineering. Similar initiatives will be undertaken at every involved institution.

Integration of knowledge transfer: integration of existing relevant centers In addition to conference presentations, journal paper publications, organizing workshops on key development areas, and summer schools, the team will broaden the impact of this center by leveraging the existing relationship of the PIs with industry partners and national laboratories. For example, UIC is home to the Energy Resources Center (ERC), an interdisciplinary public service, applied research, and special projects organization that strives to provide solutions to today's energy and environmental challenges and opportunities. The ERC will be involved in quantification efforts in Focus 1, and policy-level discussions in Focus 4. UIC's faculty have longstanding collaborations with Argonne National Laboratory which has been instrumental in many domains, including for example advancing battery technology and materials science, and the center will integrate Argonne in its research and events. The Ohio State university is home to the Translational Data Analytics Institute and Sustainability Institute, university-level large scales institutes that have a broad multi-dimansional approach to data analytics and sustainability from theory and practice to policy. co-PI Yener is affiliated faculty in both institutions in a position to leverage growing expertise into the proposed center. She also is building the 6G and Beyond Initiative. PI Gomez serves as co-director of the consortium for electromagnetics technologies at Purdue. PIs Love and Wang are the founding directors of Purdue neXt-G Center for Communications and Sensing (XGC) that has established a productive relationship with MediaTek Technology. SpectrumX is at Notre Dame, a $25M NSF-funded Spectrum Innovation Center to study spectrum management through research and workforce development. SpectrumX's director, Nick Laneman, is a senior personnel of STC^2, enabling this center to directly tap into SpectrumX's unique collaborative research environment in which faculty, students, and technical staff develop and prototype new technologies and contribute to radio spectrum policy in world-class laboratories.

E. STC^2 Institutional Commitment to Broader Participation

STC^2 aims to develop a diversity, inclusive, and culturally-sensitive program for solving these pressing science of connectivity challenges. The lead institution, UIC, and its four core partners have a strong track record of institutional commitment to broader participation. For example, UIC received an NSF ADVANCE Institutional Transformation award in 2006, with Ohio State University and Purdue following in 2008, the University of Maryland in 2010, and NCSU in 2023. UIC's award helped implement systemic changes promoting opportunities for women faculty in STEM. UIC's Vice Chancellor for Diversity, Equity, and Inclusion now reports directly to the Chancellor, underscoring the centrality of DEI to UIC's mission. Among various DEI initiatives, two are noteworthy: (i) each academic unit at UIC now has a strategic plan to Advancing Racial Equity, and progress toward unit's strategic goals is reviewed annually by the Dean, Provost and Chancellor; (ii) Bridge to the Faculty program to recruit diverse postdoctoral fellows to help them transition to tenure track faculty within two year.