Building Trust-Based Sustainable Networks

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Trust is modeled in many disciplines as a key factor in determining if entities cooperate with each other. In the social sciences, particularly within the social, economic, and environmental domains, trust has received considerable attention as the key element to building sustainable societies. However, in the networking and telecommunications fields, trust-based approaches to developing sustainable systems have yet to be examined. In this work, we study how trust can be facilitated among entities to build sustainable networks with limited resources or misbehaving entities by learning from the lessons in the social sciences. We discuss the multifaceted relationships of trust with both security and decision making. We also investigate how socio-cognitive models of trust may enhance the sustainability of a system. We discuss ways to make more intelligent interactions based on trust and economic principles.

Sustainable operations and technologies are of great relevance in recent years based on response to the growing awareness of resource limitations in the world. In particular, network-centric operations often aim to develop sustainable systems to support multiple goals [17].

Generally speaking, sustainability is defined as the capability to endure [21]. The societal viewpoint of sustainability is known as a long-term well-being that is maintained environmentally, economically, and socially. Common examples of sustainable biological systems are “long lived” and “healthy” wetlands and forests.

Linking the definitions of sustainability with trust, economists or engineers have discussed the relationship between these two concepts. Based on the economics definition of sustainability as “caring about future generations” or “inter-generational resource sharing,” Scott [18] analyzed this relationship in U.S. laws of trusts and claims that trust relationships can help responsible decision making in current and future generations under uncertainty and risk. There is some precedence in establishing a link between sustainability and trust. Charles Green, the founder of Trusted Advisor Associates, sees the relationship between trust and sustainability as a critical philosophical core value in business models [22]: “Sustainability drives Trust, which in turn drives Reputation. It’s the repeated experience over time of good practices that starts out with good reputation, but then grows into trustworthiness. And, in the long run, over time, with repeated practice, a firm that consistently does the right thing is a firm that is operating on a sustainable basis.”

In trusted computing research, Yan and Cofta [20] associated trust with sustainability by proposing a trusted computing platform for building trust sustainability based on the trust relationships among components of the proposed system. This article echoes the above definition of “sustainability” and the relationship between trust and sustainability. Many future systems may want to achieve both goals in being able to live long, be healthy, and be productive where resources are restricted. In particular, many wireless networks often face resource constraints (e.g., memory, energy, bandwidth, etc.) and security vulnerabilities while trying to maintain performance requirements (e.g., scalability, efficiency, quality-of-service) and security requirements (e.g., integrity, authentication). To build highly sustainable systems, we propose how “trust” can positively foster relationships between entities in a network to achieve sustainability by meeting both present and future goals and requirements.

In this work, we discuss the following open research questions in order to propose trust-based sustainable networks:

- How is trust related to security and decision making?
- What are the dimensions of sustainability?
- How can a socio-cognitive trust model contribute to the sustainability of a system?
- What factors affect trust emergence, propagation, and sustainability that influence relationships among entities?
- What behaviors affect trust and sustainability (e.g., altruism, reciprocation, cooperation)?

Based on these open research questions, we propose a trust-based sustainable network framework that allows a network to operate for a sustained period of time, providing adequate performance and efficiently making use of available resources.

Trust, Security, and Decision Making

Trust has been recognized as the fundamental motive to enable collaboration or cooperation among entities in networks. Most current research on trust or trust management focuses on how to measure trust more accurately under highly uncertain conditions (e.g., uncertain/incomplete information and unreliable communications). Diverse applications of trust-based schemes have proposed to use trust for improving security-related decisions in applications such as intrusion detection, access control, key management, and secure routing [6]. Attributes and properties of trust in these models have included various dimensions of entities such as the cognitive ability of humans. We restrict the scope of this work to discuss the factors that foster trust among entities...
and sustainable systems that consider evolving trust relationships between entities. For more details on how to measure trust or components of trust, readers are referred to [4], [6].

We consider how trusting and trusted behaviors are motivated by the goal of fostering trust relationships that are “sustainable” in the long term. The assumption enabling this study is that, between entities A and B, how much A trusts B also depends on how much B trusts A. That is, trust of a trustee (trusted entity) towards a trustor (trusting entity) is significantly influenced by that of the trustee towards the trustor. Trivers [16] believes that this reciprocal relationship among entities boosts trust relationships. For example, in military coalition networks, members with no prior interactions or information about each other are often required to collaborate to perform a common but complex task. In this highly uncertain environment, responses to each other can be critical to establishing trust and will impact the dynamics of their next interactions.

Multi-Dimension of Sustainability

Networks for military operations currently may have multiple system goals such as scalability, resiliency, reconfigurability (for agility), or survivability in very harsh environments due to highly constrained resources (e.g., mobile devices, wireless channels), network dynamics (e.g., mobility, terrain, and membership), selfish or malicious entities, and system heterogeneity. In order to accommodate the extreme demands of military environments, we borrow the concept of “sustainability” from healthy ecological and biological nature-inspired systems that thrive in environmental, economic, and social dimensions [1]. We propose a sustainable network to be a system that is capable of maintaining well-being by considering the following factors:

- Resource-restricted environments;
- Self-interested entities (i.e., rational behavior to maximize their individuality); and
- Misbehaving nodes in terms of environmental, economic, and social perspectives.

The sustainable network concerns current and future mission performance with the goal of maintaining the system’s performance over time. Trends in military operations show that long-term cooperation or collaboration is required among diverse groups or entities with different nationals, purposes (e.g., humanitarian or military), and cultures (local civilian, non-government organizations). Recently, these missions include counterinsurgency (COIN) operations such as humanitarian relief and refugee care. We discuss how socio-cognitive responses/reactions in relationships increase trust among entities in the network and ultimately lead to positive impact on sustainability in networks. We also note that promoting trust based on the analysis of interactions between entities should be based on methods that accurately and appropriately assign trust to other entities [7].

We define the characteristics and goals of sustainable networks, as shown in Fig. 1 [1]. Our proposed system considers resource constraints, risk, or uncertainty (e.g., less or no evidence) as the environmental factors. Performance (e.g., scalability, efficiency, quality-of-service) represents the economic factor to best utilize available resources. Security represents the social factor by being robust against attackers. Each of these factors in a network is designed with the common goal of building sustainable networks. The proposed system has the three objectives of 1) being bearable (tolerable or recoverable) against attacks or failures (i.e., resilience); 2) being viable despite penalties (e.g., some untrustworthy nodes are evicted from the system) or lack of resources (i.e., survivability); and 3) being equitable in resource sharing or allocation (i.e., fairness).

To maximize sustainability (i.e., resilience, survivability, and fairness) through trust relationships among entities in the network, we need to examine how trust can be created, fostered, and enhanced through intelligent decision making or interactions between the sub-components of the system.

Many tactical networks aiming for sustainable operations as a long-term goal also struggle with maintaining a sufficient level of performance at current times under lack of resource-restricted network environments. That is, the proposed system may have two conflicting goals: preserve its future well-being from a global system perspective and also maintain its current performance.

Fig. 1. Characteristics and goals of sustainable networks.
A tradeoff may exist between these two goals to achieve a desired level of system sustainability. Therefore, this work proposes that idea of a sustainable network where such a system quickly establishes and fosters trust, with respect to social/cognitive interactions of entities within the system. In recent work on sustainability in communication networks (e.g., wireless networks including sensor or mobile ad hoc networks), sustainability is generally used to represent survivability to optimize limited resources (i.e., battery life, bandwidth or memory) [15]. This article proposes that multiple and diverse dimensions of sustainability need to be considered to build ideal networks based on socio-cognitive models of trust.

**Socio-Cognitive Models of Trust**

A socio-cognitive model of trust integrates motivations with beliefs [4]. Motivation depends on the resultant impact of an act (i.e., a decision) on achievement of goals and social and relational consequences. We focus on how trust plays a key role in making decisions, how increased trust affects future decisions, and how interactions among entities can change the atmosphere of trust in the system. Fig. 2 shows how trust (trustor to a trustee) can be formed, aggregated, and evolved over time. The trustor is assumed to be a cognitive entity (e.g., person or intelligent agent), while the trustee can be any entity such as a person, machine, information, institution, or service [4], [12].

**Belief**

Trust is initially based on an individual’s belief with or without any initial evidence to trust or not to trust. This belief can be affected by individuals’ disposition or propensity to trust (e.g., optimistic or pessimistic, or patient or impatient, consistent or inconsistent), memory span (i.e., the period of events one uses to evaluate trust), or self-reinforcing or self-fulfilling (i.e., one may want to prove what he/she believes) towards other entities. Further, previous experiences (e.g., past friendship or collaboration) or opinions from third parties can be used to aggregate and evolve trust.

**Control**

Monitoring (e.g., direct observations) or collecting reputation or recommendations from third parties can be control mechanisms to provide feedback for the trustor to form trust of the trustee [4]. A stronger control mechanism than providing feedback can be an intervention to the current relationship of two parties to adjust, suspend, or terminate the relationship for mitigating risk or regretfulness [4]. However, when control is implemented too rigidly, trust is diminished and performance deteriorates autonomy where resources are restricted and the trustee differently behaves depending on the degree of trust the trustor has towards the trustee [14]. For example, if A tries to control B, then this may prove that A does not trust B. However, when control is employed effectively, it initiates, promotes, and enhances trust because it alleviates anxiety of the trustor or risk for possible catastrophes. When the trustor decides whether or not he/she trusts the trustee, the purpose, for example, may be delegation [4] of tasks or initiate cooperation or collaboration.

**Trusting Act**

A trusting act may be influenced by various motivations such as self-interested payoff (i.e., gains if successful, future reciprocation by the trustee), reciprocation for the past help by the trustee, or altruism [3], [16]. Besides, the trustor may misdiagnose trust (i.e., mistrust) and make a decision based on it. When the trustor decides to trust the trustee, the trustee’s act (or behavior) is also affected by various motivations such as self-confidence, reciprocation, altruism, computed reciprocation, or...
computed altruism (e.g., expecting the cooperative act will bring more benefit to future interactions).

Outcome
When the trustee behaves as the trustee expects, the trustee gains more power such as competence and more trust in the eyes of the trustor. In addition, a positive reciprocating relationship may be created, leading to enhanced trust. Moreover, trust can create social capital meaning that social networking or relationships will generate productivity in performance. All these positive products can be fed back to ensure or update the belief for the trustor to form trust in the trustee. In contrast, when the trustee does not behave as expected, the trustor feels disappointment or regretfulness, which may trigger retaliation to penalize untrustworthiness or require forgiveness to renew the relationship. Since the outcome of the trusting act also affects the initial belief to form trust in the trustee, the trust process is naturally recursive and dynamic. One key observation is that trust creates trust while distrust generates distrust based on the conjecture that an entity responds as it is treated [4].

This work captures the applications of the positive circulation of trust to build sustainable networks. In terms of multidisciplinary perspectives (e.g., psychology, ecology, or biology), altruistic or reciprocating behaviors are studied as the motive to initiate trust relationships in humans, animals, or insects [2, 16]. Although the relationship itself may be initiated involuntarily or incidentally, reciprocation creates the circulation of the positive relationship. When two entities are in a certain situation for a long time, it is observed that they may benefit more when they cooperate than when they do not [2]. In addition, altruistic behavior can trigger the reciprocal altruistic relationship, the so-called “reciprocal altruism.” In this relationship, some critical factors affect the reciprocally altruistic behavior such as duration of relationship (length of lifetime), mobility rate or pattern (disperse rate), and benefit of mutual dependence [4]. The literature summarizes that there may exist an optimal group size of animals or insects to build a reciprocally altruistic system [4]. Friendship or kinship may be the main determinants to increase altruistic behaviors. In addition, when an entity reciprocates the help it received in the past, it can reciprocate offspring of the past reciprocator even if the reciprocator does not exist [16].

Based on the insights from various disciplines as above, optimal network structures may exist to promote reciprocating behavior to foster trust relationships among entities and build a system level atmosphere of trust. These relationships can affect decisions for altruistic or reciprocal behaviors that promote trust. At the same time, reciprocation can be inherited by another entity that can be regarded as a child (or other close relationship) of the initial reciprocating entity when the initial reciprocator does not exist. This further facilitates potential of the longevity of reciprocating behaviors and trust relationships. In addition, since an entity’s resource is limited to maintain its relationships, the optimal group size or number of friends (neighbors) may exist for an entity to maximize its trust relationships. Mobility and durability of the relationship are critical factors that affect the decision making of each entity of reciprocating or altruistic acts. In the literature, as an application of reciprocation among nodes in a network, social ties are used as criteria to provide services to particular nodes in delay tolerant networks [8].

In our daily lives, we mostly make decisions based on what we gain from a relationship, commitment, cooperation, or collaboration as payoff/utility. The decision making process about whether or not to trust or cooperate can be discussed from a game theoretic perspective. Now we propose a trust-based decision making model assuming that a rational entity may want to maximize its payoff (i.e., a net gain based on the utility function of an entity) in a decision on whether to trust or not and whether to cooperate or not.

Emergence, Propagation, and Sustainability of Trust
From the economic perspective, decision making is a game. Each entity in the system has the goal to win and produce net gains by making wise decisions as a self-interested agent. Rewards and penalties are natural ways to enforce or reinforce entities’ behaviors to maximize payoffs of the system as well as those of individual entities. We look into the benefit of intelligent decision making on system sustainability in the long term while also maintaining acceptable performance in the short term. This suggests the possibility of a tradeoff, between short-term payoff (net gain) and long-term payoff.

The underlying idea of this work is based on dyadic relationships and the principle of payoffs upon decisions of each entity. Modifying the payoff theory from [10], [13] to model the relationship between a trustor and a trustee in their decision making, we show Fig. 3 as the conceptual framework that promotes trust emergence, propagation, and sustainability based on the payoff computation of each entity where two players participate in a repeated game. Note that in networks, payoffs can be interpreted as any benefit an entity may receive by the decision it makes such as accessibility to confidential information, resources, or energy savings. In each session of the game, trustor A can make its decision on whether to trust or not, and trustee B can make its decision on whether to cooperate or not.

When A has two options to choose, whether to trust or not, there exists the payoff of each decision. When A predicts its payoff as more beneficial by not trusting than trusting (i.e.,
$f(s_A) \geq f(r_A) - f(d_A)$, A will not initiate the relationship with B and its payoff remains as $f(s_A)$. However, when A predicts its payoff as more beneficial by trusting than not trusting (i.e., $f(s_A) < f(r_A) - f(d_A)$), A chooses to trust B. Then, A’s payoff depends on the action of B. If B is willing to cooperate with A based on its predicted payoff as greater benefit by being cooperative than not cooperative (i.e., $f(d_B) < f(r_B)$), A will obtain the payoff, $f(r_A)$. However, if B refuses to cooperate with A based on its predicted payoff as greater benefit by not being cooperative than being cooperative (i.e., $f(d_B) \geq f(r_B)$), A’s payoff remains as $f(d_A)$. In [10], [13], the payoff from each division is decided based on $f(d_A) = 0 < f(s_A) = f(s_B) < f(r_A) = f(r_B) < 1 = f(d_B)$. The simple net gain computations to make a decision on whether to trust or cooperate by a trustor and a trustee are summarized in Table I.

However, in practice, this payoff relationship may not hold due to dynamics or conditions of networks (e.g., durability of relationships, chances of interactions, resource constraints), complex trust relationships among entities (e.g., propensity or disposition of entities, reciprocation, altruism), or environmental or situational conditions (e.g., pressure from control mechanisms or authority to manipulate reward and penalty).

In addition, there exists uncertainty derived from incomplete, incorrect, or a lack of information. Therefore, an entity’s payoff prediction and decision based on its local information (e.g., greedy view) may not guarantee the estimated future payoff due to the uncertainty and dynamics. Jøsang [11] defines an opinion (or trust) as a subjective probability based on belief, disbelief, or/and uncertainty. Similarly, we also design the payoff based on known payoff of not trusting ($f(s_A)$), uncertainty ($f(u_A)$), known payoff of trusting ($f(r_A)$), and known payoff of being betrayed ($f(d_A)$) in terms of trustor A’s perspective. Similarly, as trustee B’s perspective, the payoff can consist of known payoff of not being trusted ($f(s_B)$), uncertainty ($f(u_B)$), known payoff of being cooperative ($f(r_B)$), and known payoff of not being cooperative ($f(d_B)$). These relations are summarized as:

$$f(s_A) + f(u_A) + f(r_A) + f(d_A) = 1$$

$$f(s_B) + f(u_B) + f(r_B) + f(d_B) = 1$$

Depending on the degree of uncertainty ($f(u_A)$ or $f(u_B)$) and any inherent errors introduced by payoff evaluation processes (e.g., perceived payoff may not be the same as actual payoff), risk of the entity’s decision is determined. Eq. (2) computes an entity’s payoff based on the importance of a game where the entity participates in a repeated game.

$$P_{payoff}(A) = \sum_{n \in S} I_A(n)P_{payoff}(A, n)$$

$$P_{payoff}(B) = \sum_{n \in S} I_B(n)P_{payoff}(B, n)$$

where

$$\sum_{n \in S} I_A(n) = 1 \quad \text{and} \quad \sum_{n \in S} I_B(n) = 1$$

$S$ is the set of game sessions that entities A and B participate and n is a game session number. Importance of a game session to an individual entity, $I_A(n)$ or $I_B(n)$, can be measured based on the impact of the outcome on the entity’s current and future goals or welfare. High importance under high uncertainty tends to generate high risk. While an entity tries to maximize its own payoff, the system concerns also its own welfare, the overall system payoff (i.e., goals), described by:

$$P_{payoff}(A, B) = \sum_{n \in S} I_{A,B}(n)P_{payoff}(A, B, n)$$

where

$$\sum_{n \in S} I_{A,B}(n) = 1$$

$I_{A,B}(n)$ is a weight for the importance of a game session to the system based on the relationship

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**Table I. Net Gain Estimation for a Decision on Whether to Trust or Cooperate**

<table>
<thead>
<tr>
<th>Decision maker</th>
<th>Condition</th>
<th>Decision made</th>
<th>Payoff</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trustor A</td>
<td>$f(s_A) \geq f(r_A) - f(d_A)$</td>
<td>Do not trust</td>
<td>$f(s_A)$</td>
</tr>
<tr>
<td></td>
<td>$f(s_A) &lt; f(r_A) - f(d_A)$</td>
<td>Trust</td>
<td></td>
</tr>
<tr>
<td>Trustee B</td>
<td>$f(d_B) \geq f(r_B)$</td>
<td>Defect</td>
<td>$f(d_B)$</td>
</tr>
<tr>
<td></td>
<td>$f(d_B) &lt; f(r_B)$</td>
<td>Cooperate</td>
<td>$f(r_B)$</td>
</tr>
</tbody>
</table>

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between A and B. $P_{\text{payoff}}(A, B)$ provides how much the payoff between A and B contributes to the overall system payoff (e.g., welfare or mission completion). As Fig. 3 shows, the act of a trustee also affects the decision of a trustor in a next session of the game.

**Sustainability and Trust**

Trust has been discussed along with other important concepts such as cooperation, altruism, reciprocation, control, etc. in order to clearly understand interactions in multiple layers of complex networks. Even if the social sciences literature gives a large volume of background knowledge for the concepts to be used in complex networks, measuring those concepts in networks may not be agreed upon easily. Moreover, there are few metrics to measure sustainability, other performance aspects (e.g., resilience, survivability, or fairness), or trust. Tradeoffs or performance analysis are shown in the literature based on perspectives from various disciplines but applying those concepts in complex networks requires significant effort to reinterpret them.

If successful, this idea gives strikingly innovative perspective to achieve ideal sustainable networks. The long-term implications of systems are enhanced through the intelligent interactions of entities to foster trust. Future networks will require a multi-level shape-shifting from a single goal oriented system to a multi-goal oriented system as proposed in this work.

These trust-based approaches to enhance the sustainability of systems pertain to applications in many networking domains. Trust can be applied to network security platforms, where traditional security approaches are too rigid. Such approaches will optimize an assumption of increased risk in potential security vulnerability while enhancing network performance. As another example, trust-based mechanisms are amenable for environmental sensing with wireless sensor networks. These mechanisms will describe intelligent approaches for data collection, providing significant benefits to sustainability or the lifetime of such systems by fine-tuning network behavior. In addition, trust-based methods are clearly applicable to human machine interaction systems or automated services. Software or agent systems can be developed to provide equitable access to particular services which are otherwise abused by misbehaving or malicious users. Such approaches provide a fair and sustainable operational lifetime. The proposed strategies rely on a long-term forward thinking perspective for the trust-based system to flourish while meeting immediate needs of the system as well.

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