Socio-aware Public Safety Framework Design: A Contract Theory based Approach

Georgios Fragkos, Nathan Patrizi, Eirini Eleni Tsiropoulou
Dept. of Electrical and Computer Engineering
University of New Mexico
Albuquerque, NM, USA
gfragkos@unm.edu, npatrizi@unm.edu, eirini@unm.edu

Symeon Papavassiliou
School of Electrical and Computer Engineering
National Technical University of Athens
Athens, Greece
papavass@mail.ntua.gr

***Abstract*—Given the substantial penetration of social networks in citizens' everyday life activities, the success of a public safety system depends on the citizens' incentivization by the Emergency Control Center (ECC), and their effective effort contribution in the overall disaster management operation. In this paper, we introduce a formal method based on the principles of Contract Theory, to identify the optimal rewards to the citizens from the ECC's perspective, and the optimal invested effort from the citizens' side, referred to as contract pairs. The identification of these contract pairs (i.e., rewards and respective efforts) between the ECC and each citizen, depend on each citizen's social and communication characteristics that are used to define their specific type and profile, while they are properly reflected in the corresponding designed utility functions to be optimized. The problem under consideration is treated for both cases of complete (ideal) and incomplete (realistic) information availability, with respect to the level of knowledge of the ECC about the exact type of each citizen. The overall framework was evaluated via modeling and simulation, in terms of its efficiency and effectiveness, by studying multiple operation approaches and scenarios.**

***Index Terms*—Contract Theory, Socio-aware Public Safety, Effort Investment, Citizen Incentivization**

I. Introduction

In public safety events, either natural disasters or terrorists attacks, the engagement of the citizens, the knowledge discovery, and the information dissemination play a critical role throughout the overall disaster management operation. Nowadays, social networks have become of paramount importance in preparedness, emergency control management, response, and recovery. Millions of citizens depend on and exploit various social networks, such as Facebook, Weibo, Twitter, and others to spread information about critical events. This process in turn helps the Emergency Control Centers (ECC) to improve the disaster management operation. An indicative example is the "Boston Marathon" event in 2013, where the image of the suspect was retrieved from the social networks [1]. However, rumors and false information can also be disseminated in social networks and harm the rescue process in a public safety system [2]. Therefore, the classification, capabilities and interactions of the involved actors in the socio-aware public safety systems are of high significance.

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Motivated by the aforementioned observations, in this paper, we introduce a socio-aware public safety system, where the types of citizens offering information to the ECC are identified based on their social and communication characteristics. The ECC motivates the citizens to participate in the disaster management operation by offering to them incentives (e.g., benefits, coupons) in accordance to their types under information asymmetry or complete information, while the citizens contribute their personal effort to the process in order to improve the disaster management operation. To this end, we adopt *Contract Theory*, a powerful tool from microeconomics to model the citizens' incentive mechanism, through the use of contracts (agreements) between the ECC and the citizens. The ultimate goal is to find the optimal contract pair of ECC's offered reward and each citizen's provided effort based on its socio-communication profile and type.

A. Related Work

The actual and potential exploitation and impact of social networks on emergency disaster management and crisis situation has been studied in [3] to identify the benefits, e.g., monitoring situations, extending emergency response and management, as well as the negative developments, such as disseminating rumors. In [4], the authors introduce the concept of People as Sensors, where people contribute information through the social networks and their provided information is integrated within the location-based services, data analysis, and visualization systems. This concept is further extended in [5], where a tutorial of models and algorithms is presented for interactive sensing in social networks, where the users' provided information is exploited to optimize sensing, decision-making, and operations in dynamic environments, such as the public safety systems. Furthermore, a multimedia content analysis of the available information in social networks is introduced in [6] in order to detect events, e.g., natural disasters and terrorists' attacks, and manage the corresponding rescue operations.

Based on the above, it is evident that a great part of the available literature deals with the exploitation of the already available information in the social networks in order to detect public safety events and provide input to the disaster management operations. However, limited research has been performed in the area of properly modeling and exploiting the incentivization of the citizens in order to provide valuable information in the social networks that will support the ECC's operations. Towards this direction, some initial efforts have been devoted to encouraging citizens to report public safety problems, by capitalizing on the concepts of crowdsourcing, incentivization and volunteer computing [7], [8]. Nevertheless, the majority of them have been relatively primitive focusing primarily on finding ways of simply engaging citizens, being either heuristic or crude in their nature, without attempting to quantify the contribution of each citizen in a formal manner.

In this paper, we adopt concepts and principles of *Contract Theory*, which provides the mathematical foundations to design formal and informal agreements to motivate people with potentially conflicting interests to take mutually beneficial actions, which otherwise would be counter-productive. Under this concept, an employer provides contracts to the employees based on their profiles, i.e., types, to motivate them to provide back their effort, which is crucial for the employer's operational processes.

Contract theory has been already applied in several communication-related applications, including device-to-device (D2D) communications and cooperative spectrum sharing. In particular, in [9], the authors introduce a contract-theoretic relay selection framework, where the employer is the transmitter and the employees are the relay nodes. The transmitter offers rewards, i.e., payments, to the employees, while the latter guarantee a signal-to-interference-plus-noise-ratio at the destination. Contract theory has been also used to incentivize the users, i.e., employees, to establish device-to-device communication pairs to de-congest their communication with the base station (i.e., employer) [10]. Also, contract theory is used in cooperative spectrum sharing [11], and in cognitive networks allowing the primary spectrum owner (i.e., employer) to incentivize the secondary users (i.e., employees) to efficiently share the available bandwidth [12].

B. Contributions & Outline

This paper aims exactly at filling the aforementioned research gap, by introducing formal methods - based on the Contract Theory - in order for the ECC to incentivize the citizens to participate in the disaster management operations and offer their valuable effort and information in an optimal manner. The key scientific contributions of our work that differentiate it from the rest of the existing literature, are summarized as follows.

1. The different types of the citizens are identified by the ECC via exploiting their social and communication characteristics, and identify a socio-communication type for each citizen. Based on the citizen's type, a corresponding utility is formulated reflecting its perceived satisfaction from the received reward for its invested effort. Also, the ECC's utility is defined to capture the overall benefit of using the citizens' efforts, while considering the corresponding cost of providing incentives to the citizens through the rewards. A contract pair between the ECC and each citizen is considered to be established consisting of the ECC's reward and the citizen's effort (Section II).

2. The problem of determining the optimal rewards from the ECC's perspective and the optimal invested effort from the citizens' side is formulated and solved initially considering that the ECC has complete information about the types of the citizens (Section III). Furthermore, the aforementioned problem is addressed and thoroughly analyzed, under the most challenging and realistic assumption of ECC's incomplete information knowledge about the citizens' types (Section IV). In both scenarios, the outcome of the proposed framework is the optimal contract pairs.

3. A series of simulation experiments are realized to evaluate the performance and inherent attributes of the proposed socio-aware public safety framework (Section V). Finally, Section VI concludes the paper.

II. System Model

We consider a public safety system consisting of an Emergency Control Center (ECC) that is responsible to coordinate the disaster management operations and a set of citizens $C = \{1, \dots, c, \dots, |C|\}$. The ECC rewards the citizens through personalized rewards r_c (e.g., benefits, coupons, money) in order to incentivize them to provide their valuable effort in the disaster management operations. The citizen's effort q_c can capture various types of effort: (a) social related effort, such as data quality (e.g., sensing data, closed cameras TV data), information shared in social networks, influential posts on Twitter, shelters' announcements on Facebook, and others, and (b) communication related effort, such as coverage area of the citizen's mobile device, which can potentially act as a relay node, CPU capability provided by the citizen's devices to process data in a fog computing setup and others. We consider the normalized values of the ECC's rewards, i.e., $r_c \in [0, 1]$, and the citizen's effort, i.e., $q_c \in [0, 1]$. Also, the ECC acts in a fair manner and rewards more the citizens that provide more effort in the disaster management operation, thus the reward r_c is a strictly increasing function with respect to the citizen's effort q_c.

A. Citizen's Social and Communication Type

Each citizen is characterized by a socio-communication type t_c which captures its social and communication characteristics in terms of providing information to the ECC. Regarding the communication characteristics, each citizen achieves a data rate $R_c = Wlog(1 + \frac{P_c g_c}{\sum_{i \neq c} P_i g_i + I_0})$ to directly report information to the ECC's receiver, where W is the system's bandwidth, P_c and g_c are the citizen's transmission power and channel gain, respectively, $\sum_{i \neq c} P_i g_i$ is the overall sensed interference, and I_0 is the background noise. It is evident that the greater the citizen's achievable data rate is, the more valuable it becomes for the ECC's operation as more information can be collected by the ECC.

Moreover, the citizen's socio-communication type is also dependent on its social characteristics. Each citizen is characterized by its reputation score $\mu_c, \mu_c \in [0, 1]$, based on its activity in the social networks, i.e., information spread. The citizen's information spread is modeled in the literature by the diffusion model and the influence maximization algorithms can be used to determine the reputation score μ_c (i.e., identify the influential citizens) [13]. A citizen's contribution to the information spread process, is characterized by a corresponding social impact $SI_c(\mu_c)$ to the community, which is assumed a strictly increasing function with respect to the citizen's reputation score. Furthermore, to also capture the importance of the citizen's information contribution for the disaster management operation of the ECC, we introduce the concept of knowledge discovery $KD_c, KD_c \in [0, 1]$, referring to the unique content that the citizen shares to the social network or offers directly to the ECC compared to a bulk amount of data.

Based on the aforementioned citizen's social and communication characteristics, the socio-communication type $t_c, t_c \in [0, 1]$ of the citizen is defined as follows.

$$t_c = \frac{R_c}{\sum_{\forall i \in C} R_i} \cdot \frac{SI_c(\mu_c)}{\sum_{\forall i \in C} SI_i(\mu_i)} \cdot KD_c \qquad (1)$$

For demonstration purposes, we also consider a strictly increasing function $r_c(q_c) = t_c q_c$ regarding the ECC's reward for citizen c. Also, in the following analysis, we consider $|C|$ different types of citizens, that is each citizen has a unique socio-communication type, while a citizen of higher type, i.e., $t_1 < \cdots < t_c < \cdots < t_{|C|}$, provides more effort q_c, i.e., $q_1 < \cdots < q_c < \cdots < q_{|C|}$.

B. Emergency Control Center's and Citizens' Utilities

The ECC offers a personalized contract pair $\{r_c(q_c), q_c\}$ to the citizen c for its provided effort q_c by providing a corresponding reward r_c. Each citizen is characterized by a utility function $U_c(q_c)$ expressing the perceived satisfaction from the ECC's provided reward based on its socio-communication type, as well as its cost to provide its effort that the citizen has invested in the disaster management operation. The citizen's utility is defined as follows.

$$U_c(q_c) = t_c \cdot e(r_c) - q_c \qquad (2)$$

where $e(r_c)$ is the evaluation function of the citizen c regarding the received reward r_c. The evaluation function $e(r_c)$ is a strictly increasing, concave function with respect to the citizen's effort q_c, with $e(r_c = 0) = 0$ and expresses the citizen's satisfaction with respect to the reward that it received. For demonstration purposes and without loss of generality, in the following we consider $e(r_c) = \sqrt{r_c}$.

The ECC also experiences a utility $U^c_{ECC} = q_c - \kappa \cdot r_c$ by each citizen's provided effort, while taking into account the corresponding cost of the reward r_c (κ is the ECC's pricing factor). In the general case, the ECC may not be aware of the citizen's types, thus the ECC estimates them with probability p_c, where $\sum_{c=1}^{|C|} p_c = 1$. Thus, the ECC's overall perceived utility (accounting for all citizens) is defined as follows.

$$U_{ECC}(\mathbf{q}) = \sum_{c=1}^{|C|} [p_c(q_c - \kappa \cdot r_c)] \qquad (3)$$

where $\mathbf{q} = (q_1, \ldots, q_{|C|})$ is the vector of the citizens' effort.

Considering the overall socio-aware public safety system, its social welfare, including both the ECC and all the citizens, is defined as follows.

$$SW(\mathbf{q}) = U_{ECC}(\mathbf{q}) + \sum_{c=1}^{|C|} U_c(q_c) \qquad (4)$$

C. Contract Theory Perspective and Methodology

Based on the aforementioned utilities, rewards and other related parameters, in general the solution we seek is a set of contract pairs between the ECC and the citizens (employer and employees under Contract Theory terminology [14]) with reference to the citizen's effort q_c and the corresponding provided reward r_c, with the objective being maximizing the employer's utility. The problem is typically formulated as maximizing an objective function that represents the employer's utility, subject to the incentive compatibility constraint that the employee's expected utility is maximized when accepting the personalized contract, and the individual rationality constraint that the employee's utility under this contract is larger than or equal to its counterpart when not participating (the latter concepts are described formally and more detailed in Section III and Section IV below).

Contract theory is used to study the interaction between employer(s) and employees, and treats real world problems with either complete or even incomplete (often referred to as asymmetric information), by formally designing the contract between employer and employee, while implicitly introducing cooperation. The information asymmetry mainly refers to the fact that the employer does not know exactly the types and therefore the characteristics of the employees, and has only knowledge about the probability distribution of the types of employees. Contract-theoretic models allow the alleviation of this problem, and accordingly the employer can overcome this asymmetricity and efficiently still incentivize its employees. In the following sections we address the identification of optimal contract pairs between the ECC and citizens, for both cases of complete and incomplete information availability.

III. Citizens' Contracts under Complete Information

In this section, the ideal case where the ECC knows a priori the type of each citizen is considered. In this scenario which can be mainly used for benchmarking purposes, the ECC can fully exploit the citizens' efforts and make the best out of them regarding the disaster management operation. Thus, the ECC aims at maximizing its perceived utility by the effort of each citizen, while guaranteeing that the latter will accept the offered contract, i.e., the ECC has to ensure that the individual rationality condition of each citizen is satisfied. Therefore, the problem of determining the optimal contracts, under the assumption of complete information of the citizens' socio-communication types, can be written as follows.

$$\max_{\{r_c(q_c),q_c\}_{\forall c\in C}} U^c_{ECC} = q_c - \kappa \cdot r_c, \qquad \forall c \in C \tag{5a}$$

$$s.t. \qquad t_c \cdot e(r_c) - q_c \geq 0 \tag{5b}$$

The ECC will target at providing the minimum acceptable utility to the citizens towards maximizing its own utility. Thus, the constraint (5b) can be considered alternatively as equality in this case. Accordingly the solution of the optimization problem (5a)-(5b) is obtained by initially solving the equality (5b) with respect to r_c, and subsequently performing basic mathematical treatment and manipulations (i.e., substituting in (5a), differentiating Eq. (5a) with respect to q_c, and equating the outcome to zero). Consequently, under the assumption of complete information availability at the ECC, with respect to the exact type of each citizen and therefore its characteristics, the optimal contract pair is given by the following closed form solution: $\{r_c(q_c), q_c\} = \{(\frac{t_c}{2\kappa})^2, \frac{t_c^2}{2\kappa}\}$.

IV. Contract Theoretic Public Safety Systems under Incomplete Information

In this section, we extend our study in determining the optimal contract pairs $\{r_c(q_c), q_c\}$ between the ECC and the citizens, under the realistic scenario of incomplete information availability, that is the ECC is not aware of the exact type of each citizen (i.e., information asymmetry). Nevertheless, the ECC should ensure two conditions for the citizens, i.e., individual rationality (IR) and incentive compatibility (IC), in order to guarantee their participation in the disaster management operation. The IR constraint refers to guaranteeing that the citizens will receive a non-negative utility by accepting the contract, thus, they will be at least willing to participate in the disaster management operation, while the IC constraint ensures that each citizen will receive the contract that better matches its type. The aforementioned conditions can be formally stated as follows.

Definition 1: (Individual Rationality (IR)) A contract pair $\{r_c(q_c), q_c\}$ should guarantee that each citizen's utility is non-negative, i.e., $U_c(q_c) = t_c \cdot e(r_c) - q_c \geq 0, \forall c \in C$.

Definition 2: (Incentive Compatibility (IC)) Each citizen must select the contract pair $\{r_c(q_c), q_c\}$ designed for its type, i.e., $t_c \cdot e(r_c) - q_c \geq t_c \cdot e(r_{c'}) - q_{c'}, \forall c, c' \in C, c \neq c'$.

The IR and IC constraints are necessary, but not sufficient in order the ECC to determine the optimal contract pairs. Additionally, the following conditions and properties must hold true in order the contract pairs to be feasible.

Proposition 1: For any feasible contract pair $\{r_c(q_c), q_c\}$, the following property must hold true: $r_c > r_{c'} \Leftrightarrow t_c > t_{c'}$ and $r_c = r_{c'} \Leftrightarrow t_c = t_{c'}$.

Proof: Initially, we prove the sufficiency of the above property by using the IC constraint, i.e., $t_c \cdot e(r_c) - q_c \geq t_c \cdot e(r_{c'}) - q_{c'}, \forall c, c' \in C, c \neq c'$. Thus, we want to show $t_c > t_{c'} \Rightarrow r_c > r_{c'}$. Based on the IC constraint, we have:

$$t_c \cdot e(r_c) - q_c \geq t_c \cdot e(r_{c'}) - q_{c'} \tag{6}$$

$$t_{c'} \cdot e(r_{c'}) - q_{c'} \geq t_{c'} \cdot e(r_c) - q_c \tag{7}$$

By adding the inequalities (6) and (7), we have:

$$t_c e(r_c) + t_{c'} e(r_{c'}) \geq t_c e(r_{c'}) + t_{c'} e(r_c) \tag{8}$$

By continuing the derivations in inequality (8) and given that $t_c > t_{c'}$ and $e(r_c)$ is a strictly increasing function with respect to r_c, we conclude that $r_c > r_{c'}$. Continuing our analysis, we prove the necessity of the examined property, i.e., $r_c > r_{c'} \Rightarrow t_c > t_{c'}$. We have $r_c > r_{c'}$, and given that $e(r_c)$ is a strictly increasing function, we conclude that $e(r_c) - e(r_{c'}) > 0$. Based on Eq. 8, we have $t_c[e(r_c) - e(r_{c'})] \geq t_{c'}[e(r_c) - e(r_{c'})] \Leftrightarrow [t_c - t_{c'}][e(r_c) - e(r_{c'})] \geq 0$, thus $t_c > t_{c'}$. Similar analysis can be followed for the property $r_c = r_{c'} \Leftrightarrow t_c = t_{c'}$. ∎

The physical meaning of Proposition 1 is that a citizen of higher type t_c will receive a higher reward r_c compared to a citizen of lower type $t_{c'}$, who will receive lower reward $r_{c'}$. Proposition 1 guarantees the fairness in the rewards allocation from the ECC to the citizens.

Proposition 2: (Monotonicity) A citizen of higher type, i.e., $t_1 < \cdots < t_c < \cdots < t_{|C|}$, will receive a greater reward from the ECC, i.e., $r_1 < \cdots < r_c < \cdots < r_{|C|}$, as it will contribute a greater effort, i.e., $q_1 < \cdots < q_c < \cdots < q_{|C|}$.

Proof: The proof of this proposition intuitively stems from Proposition 1, given that $t_1 < ... < t_c < ... < t_{|C|}$. ∎

In the following proposition, we examine the perceived utility of the citizens that have different socio-communication types.

Proposition 3: A citizen of higher type, i.e., $t_1 < \cdots < t_c < \cdots < t_{|C|}$, will receive a higher utility, i.e., $U_1 < \cdots < U_c < \cdots < U_{|C|}$.

Proof: We examine two citizens $c, c' \in C$ of types $t_c > t_{c'}, c \neq c'$. Based on the IC constraint, we have $t_c \cdot e(r_c) - q_c \geq t_c \cdot e(r_{c'}) - q_{c'} \xrightarrow{t_c > t_{c'}} U_c(q_c) = t_c \cdot e(r_c) - q_c > t_{c'} \cdot e(r_{c'}) - q_{c'} = U_{c'}(q_{c'})$. Thus, for $t_1 < \cdots < t_c < \cdots < t_{|C|}$, we conclude that $U_1 < \cdots < U_c < \cdots < U_{|C|}$. ∎

Based on the above introduced models, constraints, and the application of the key principles of Contract Theory, the ECC aims at maximizing its utility, while the citizens should satisfy all their personal constraints in order to be willing to participate in the socio-aware public safety system. Thus, optimization problem to determine the optimal contract pairs $\{r_c(q_c), q_c\}, \forall c \in C$ between the ECC and the citizens is formulated as follows.

$$\max_{\{r_c(q_c),q_c\}_{\forall c \in C}} U_{ECC}(\mathbf{q}) = \sum_{c=1}^{|C|}[p_c(q_c - \kappa \cdot r_c)] \quad (9a)$$

$$s.t. \qquad t_c \cdot e(r_c) - q_c \geq 0, \forall c \in C \quad (9b)$$

$$t_c \cdot e(r_c) - q_c \geq t_c \cdot e(r_{c'}) - q_{c'}, \forall c, c' \in C, c \neq c' \quad (9c)$$

$$0 \leq r_1 < \cdots < r_c < \cdots < r_{|C|} \quad (9d)$$

Given that the above optimization problem is non-convex, in the following we reduce its constraints in order to solve it in a tractable manner. Based on Proposition 2, we have $t_1 < \cdots < t_c < \cdots < t_{|C|}$ and considering the IC constraint, we have $t_c \cdot e(r_c) - q_c \geq t_c \cdot e(r_{c'}) - q_{c'} \geq t_c \cdot e(r_1) - q_1$. Given that $t_c > t_1$, we have: $t_c \cdot e(r_c) - q_c \geq t_c \cdot e(r_1) - q_1 \geq t_1 \cdot e(r_1) - q_1 \geq 0$. The last step of the latter inequality stems from the IR constraint (9b). Thus, if $t_1 \cdot e(r_1) - q_1 \geq 0$ holds true, then $t_c \cdot e(r_c) - q_c \geq 0$ holds true for each citizen $c \in C$. The above analysis concludes to the observation that if the IR constraint holds true for the citizen with the lower type, i.e., t_1, then it will hold true for any other citizen of higher type, thus, the IR constraints are reduced to $t_1 \cdot e(r_1) - q_1 = 0$. The latter IR constraint is considered as equality in order to the ECC to collect the maximum benefit from the citizen's effort.

In the following analysis, we target at reducing the IC constraints. The terminology that we use about the IC constraints between citizens: (a) $c, c', c' \in \{1, \ldots c-1\}$ is downward IC constraints, (b) $c, c', c' \in \{c+1, \ldots |C|\}$ is upward IC constraints, (c) $c, c-1, \forall c, c-1 \in C$ is local downward IC constraints, and (d) $c, c+1, \forall c, c+1 \in C$ is local upward IC constraints.

Proposition 4: All the downward IC constraints can be represented by the local downward IC constraints.

Proof: Considering three types of citizens: $t_{c-1} < t_c < t_{c+1}$, the local downward IC constraints can be written as:

$$t_{c+1} \cdot e(r_{c+1}) - q_{c+1} \geq t_{c+1} \cdot e(r_c) - q_c \quad (10)$$

$$t_c \cdot e(r_c) - q_c \geq t_c \cdot e(r_{c-1}) - q_{c-1} \quad (11)$$

Based on Proposition 1, we have $r_c > r_{c'} \Leftrightarrow t_c > t_{c'}$. For $r_c > r_{c-1} \overset{e \nearrow}{\Longleftrightarrow} e(r_c) > e(r_{c-1}) \Leftrightarrow e(r_c) - e(r_{c-1}) > 0$. Thus, for $t_{c+1} > t_c \Leftrightarrow t_{c+1}[e(r_c) - e(r_{c-1})] > t_c[e(r_c) - e(r_{c-1})] \geq^{(11)} q_c - q_{c-1}$. Therefore, we have recursively: $t_{c+1} \cdot e(r_{c+1}) - q_{c+1} \geq t_{c+1} \cdot e(r_{c-1}) - q_{c-1} \geq t_{c+1} \cdot e(r_{c-2}) - q_{c-2} \geq \cdots \geq t_{c+1} \cdot e(r_1) - q_1$. Thus, all the downward IC constraints can be equivalently captured by the local downward IC constraints:

$$t_c \cdot e(r_c) - q_c \geq t_c \cdot e(r_{c-1}) - q_{c-1} \quad (12)$$

■

Proposition 5: All the upward IC constraints can be represented by the local downward IC constraints.

Proof: Based on the IC constraint, we have:

$$t_{c-1} \cdot e(r_{c-1}) - q_{c-1} \geq t_{c-1} \cdot e(r_c) - q_c \quad (13)$$

$$t_c \cdot e(r_c) - q_c \geq t_c \cdot e(r_{c+1}) - q_{c+1} \quad (14)$$

Based on Proposition 1, we have $r_c > r_{c'} \Leftrightarrow t_c > t_{c'}$. Thus, based on Eq. 14, we have:

$$q_{c+1} - q_c \geq t_c[e(r_{c+1}) - e(r_c)] \geq t_{c-1}[e(r_{c+1}) - e(r_c)] \quad (15)$$

given that $t_c > t_{c-1}$. Based on Eq. 13, 15, we have: $t_{c-1}e(r_{c-1}) - q_{c-1} \geq t_{c-1}e(r_c) - q_c \geq t_{c-1}e(r_{c+1}) - q_{c+1}$. Thus, we have: $t_{c-1}e(r_{c-1}) - q_{c-1} \geq t_{c-1}e(r_{c+1}) - q_{c+1}$. Thus, if the IC constraint holds true for the citizen of type t_{c-1}, then all the upward IC constraints hold true. Therefore, we have recursively: $t_{c-1} \cdot e(r_{c-1}) - q_{c-1} \geq t_{c-1} \cdot e(r_{c+1}) - q_{c+1} \geq \cdots \geq t_{c-1} \cdot e(r_{|C|}) - q_{|C|}$. Based on the above analysis, we conclude that the local upward IC constraints and all the upward IC constraints can be reduced to the local downward IC constraints. ■

Based on the reduced IR constraints, and Propositions 4 and 5, the optimization problem (9a)-(9d) can be rewritten to the following convex optimization problem.

$$\max_{\{r_c(q_c),q_c\}_{\forall c \in C}} U_{ECC}(\mathbf{q}) = \sum_{c=1}^{|C|}[p_c(q_c - \kappa \cdot r_c)] \quad (16a)$$

$$s.t. \qquad t_1 \cdot e(r_1) - q_1 = 0, \forall c \in C \quad (16b)$$

$$t_c \cdot e(r_c) - q_c = t_c \cdot e(r_{c-1}) - q_{c-1} \quad (16c)$$

$$0 \leq r_1 < \cdots < r_c < \cdots < r_{|C|} \quad (16d)$$

The optimization problem (16a)-(16d) is solved using standard methods of convex optimization due to the convexity of the objective function and the constraints [15], and the optimal contract pairs $\{r_c(q_c), q_c\}$ are determined.

V. Numerical Results

In this section, a detailed numerical evaluation of the proposed contract-theoretic socio-aware public safety approach is conducted, via modeling and simulation. The performance evaluation initially focuses on the pure operation of the proposed framework in terms of determining the optimal contract pairs, the citizens' and the ECC's utilities, as well as the overall social welfare of the system, for both cases of complete and incomplete information availability (Section V-A). Then, a comparative study of the proposed contract-theoretic framework against different alternative scenarios of determining the amount of effort offered by the citizens is presented (Section V-B).

In the rest, we consider $\kappa = 0.999$, and that the probabilities of the citizens' types follow a uniform distribution. Moreover, the achievable data rate R_c is determined for each citizen considering a constant data transmission power $P_c = 2Watts$, the channel gain is $g_c = 1/d_c^2$, where

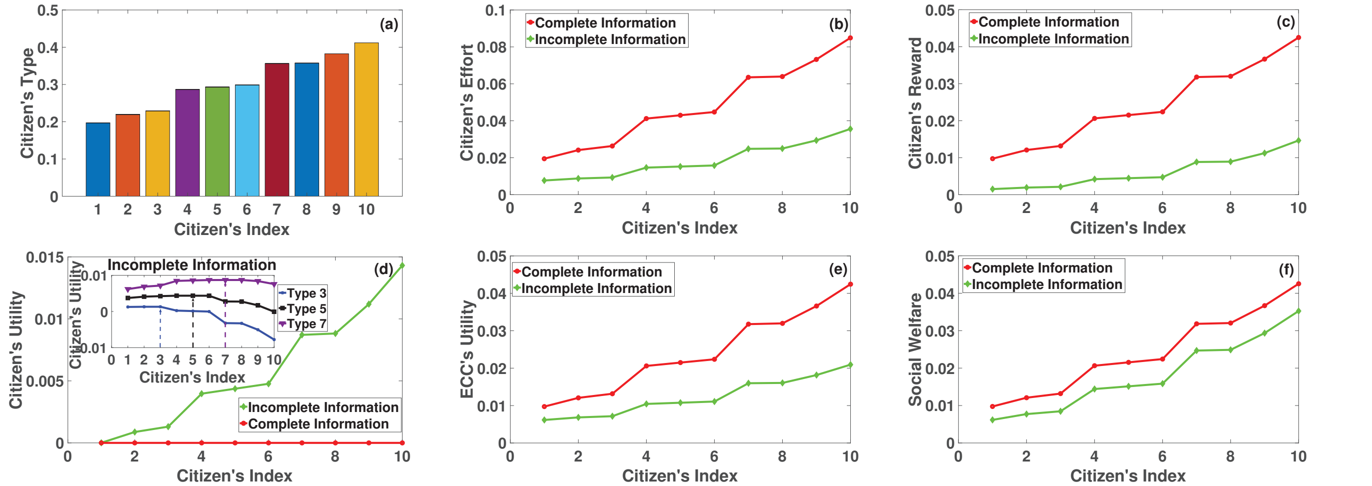

Fig. 1: Pure Framework Evaluation - Complete and Incomplete (Asymmetric) Information Scenarios

$d_c \in [10, 400]m$ is the distance of the citizen c from the ECC's receiver, the sytem's bandwidth is $W = 5MHz$, and the background noise is $I_0 = 10^{-13}$. The reputation score $\mu_c, \mu_c \in [0, 1]$ is appropriately calculated following the influence maximization algorithm [13]. The social impact function is $SI(\mu_c) = log(\mu_c)$, and the knowledge discovery factor KD_c takes random values in the interval $[0, 1]$, where values closer to one indicate that the citizen has provided unique and valuable content to the ECC.

A. *Pure Framework Operation Evaluation*

Fig. 1.a presents the citizens' type values as a function of their index. We considered $|C| = 10$ indicative citizens, where the greater the citizen's index is the higher its type, i.e., $t_1 < \cdots < t_c < \cdots < t_{10}$. Fig. 1.b-1.d present the citizens' efforts, their offered rewards by the ECC and their achieved utilities as a function of the citizen's index, respectively, considering the scenarios of complete and incomplete information. Similarly, Fig. 1.e-1.f demonstrates the system's point of view, by presenting the ECC's utility and the system's social welfare, in a cumulative manner as the number of contributing citizens increases (each time inserting one additional citizen type indicated by the increased indices in the horizontal axis).

The results reveal that under the scenario of complete information (i.e., ideal scenario), the ECC knows a priori the socio-communication type of each citizen, thus, it fully exploits the citizens' effort (Fig. 1.b) by providing increased rewards to them (Fig. 1.c), and achieving high ECC utility due to the increased citizens' participation (Fig.1.e). Given that the ECC knows the citizens' types, it offers them the minimum possible reward based on their invested efforts in order to marginally satisfy their rationality constraints, thus $U_c = 0, \forall c \in C$ (Fig. 1.d).

On the other hand, under the incomplete information scenario, the ECC is not aware of the citizens' actual types, but it rather estimates them based on the knowledge about their probability distribution. In this case, the citizens by not disclosing their actual type to the ECC are able to achieve a higher utility compared to the complete information scenario (Fig. 1.d), i.e., tradeoff between their invested efforts (Fig. 1.b) and their rewards from the ECC (Fig. 1.c). Consequently, the ECC achieves lower utility compared to the complete information scenario (Fig. 1.e). The sub-graph in Fig. 1.d shows that citizens' of higher type receive higher utility and the contract that matches the citizen's type concludes to the best achieved utility.

In a nutshell, based on Fig. 1.a-1.d, it is confirmed that a citizen of higher type, invests more effort, receives more reward from the ECC, and consequently achieves greater utility, as also stated in Proposition 2. Moreover, in Fig. 1.f, we observe that despite the fact that under the incomplete information scenario the ECC is not aware of the exact type of each citizen, the achieved overall public safety system's social welfare is reduced only by approximately 15% for the case of $|C| = 10$ citizens (this value becomes even smaller for larger populations), which indicates that the proposed framework behaves very well under the challenging and realistic asymmetric scenario.

B. *Comparative Evaluation*

Fig. 2.a-2.c compares the proposed incomplete information realistic contact-theoretic framework's achieved ECC's utility, citizens' utilities, and overall system's social welfare, respectively, against three alternative strategies with respect to the citizen's effort investment, as follows: (i) minimum effort, (ii) maximum effort, and (iii) a random amount of effort. The results reveal that under the proposed framework the citizens are able to achieve high utility, similar to the one achieved by their minimum personal effort strategy (Fig. 2.b). Also, as expected, the ECC achieves the maximum utility if all the citizens invest their maximum effort (Fig. 2.a). However, despite the fact that ECC achieves low utility under the proposed contract-theoretic approach due to the cost of increased provided rewards to the citizens (owing to the information

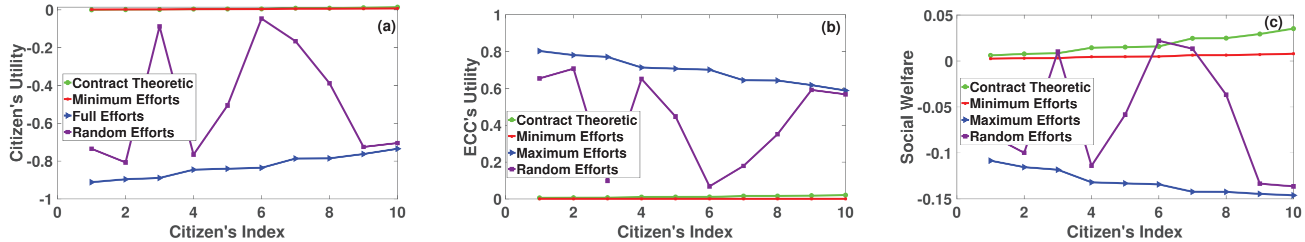

Fig. 2: Comparative Evaluation

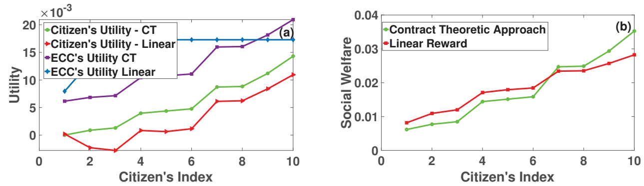

Fig. 3: Type dependent vs. type agnostic rewards

incompleteness assumption), the system's social welfare is the highest among all scenarios (Fig. 2.c). The latter shows that the proposed framework enables the smooth collaboration between the ECC and the citizens, concluding to improved social welfare. Finally, the scenario where the citizens invest a random effort presents an intermediate trend regarding all the examined metrics, between the minimum and the maximum invested efforts scenarios.

In the following we compare the strategy where the ECC offers personalized rewards to the citizens (according to their type as realized in the proposed framework, i.e., $r_c = t_c \cdot q_c$), against an alternative still linear but type agnostic reward approach, offering common reward to all the citizens, i.e., $r_c = \frac{\sum_{c=1}^{|C|} t_c}{|C|} \cdot q_c$. We observe that the citizens benefit in terms of their achieved utility under the contract-theoretic (CT) framework, while the ECC achieves lower utility compared to the linear reward scenario, as in the latter case it tends to over-reward the citizens without adopting to their socio-communication type (Fig.3.a). We also observe that the contract-theoretic framework achieves higher system's social welfare (Fig. 3.b), exceeding by approximately 25% the corresponding values under the linear reward framework.

VI. Conclusions

In this paper, a socio-aware public safety framework founded on the properties of contract theory is proposed, in order to determine the optimal contract pairs between the ECC and the citizens, towards incentivizing the latter to participate in the disaster management operation. The citizens are characterized by their socio-communication type, capturing both their activity in the social networks and their communication characteristics. The citizens provide their efforts to the ECC, which in return rewards them. The identification of the optimal contract pairs, i.e., ECC's rewards and citizens' efforts, have been provided under the scenarios of both complete and incomplete information, with respect to the ECC knowledge about the actual type of each citizen.The overall framework was evaluated via modeling and simulation, in terms of its efficiency and effectiveness, by studying multiple operation approaches and scenarios.

Part of our current and future work contains the extension of this model under the principles of Prospect Theory, towards capturing the citizens' behavioral characteristics in their utilities under risks and uncertainty, and their corresponding impact on the optimal contract pairing.

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