Game-Theoretic Models of Electricity Theft Detection in Smart Utility Networks
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“Historically, widespread energy theft is characteristic for developing countries, with theft of electricity reaching up to 50% in some jurisdictions.”
Types of Electricity Theft, or “Nontechnical Losses”

- Errors of utility personal or an operator (human error, honest mistakes)
- Customer theft
- Customer non-payment
- Theft by noncustomers
Ways of Recovering Nontechnical Losses

• Imposing higher electricity tariffs on paying customers
• Decreasing profit margins of the distributor (usually a regulated monopoly, due to the physical requirements of distributing electricity)
• Distributing the burden to the entire society using taxes
Meter Data Management (MGM)

- Span the range of very simple (this paper) to complex machine learning techniques
- Does not have the capability of catching illegal line-taps, just meter tampering
  - Paper did not acknowledge this
This Paper’s Goal

- Goal of this paper is not to develop an advanced learning technique, but to evaluate the monitoring choices for any given detection technique.
- Uses game theoretic models to model the adversarial nature of consumers and distributors regarding theft detection.
- The game is a leader-follower game in which the distribution authority is the leader chooses the prices and how much to spend on theft pursuit, given
The Game

• Leader-follower game

• Leader: Distribution authority
  – know just the percentage of its customers that are fraudulent
  – Chooses the prices, penalties, and how much to spend on theft pursuit

• Follower: Customers who are in a position to be fraudulent due to meter quality, network defects
  – Know prices, penalties, and how much utility is spending on theft pursuit
  – Choose how much power to buy and/or steal

• Considers two environments:
  – Unregulated Monopoly
  – Perfect Competition
Explicit Assumptions

• All customers are either f-type or g-type
  – f-type customers are in a position where it is easy to steal (cheap meter, unprotected grid)
  – g-type customers are not in a position where they can steal electricity
• g-type customers all share utility function, f-type customers all share a utility function
• Every customer has the same u preferences
• Distributor knows the percentage of f-type to g-type for the whole network, but not can’t distinguish on an individual basis
• Monitoring and enforcement cost $
• Meter measurements for g-type customers are i.i.d. exponentially distributed (also looks at gaussian distribution)
• f-type could be subject to fines unfairly if they are a false positive (charged for power they didn’t steal)
  – So it is not necessarily better to be an f-type or g-type
Implicit Assumptions

• All customers have the same ethics and are utility maximizers → no ethics
• Behavior is only a product of the market, no other factors (e.g. peer pressure, fear) are relevant
Exponential Distributions and ROC Curves

**FIGURE 2** The computation of detection probability $\rho_D$ and false alarm probability $\rho_F$.

**FIGURE 3** Received operating characteristic curves ($\rho_D$ versus $\rho_F$) for different levels (that is, $q_i^s/q_g \times 100\%$) of stealing by type-f customers.
Better to be f-type or g-type?

**FIGURE 5** Isolines of 60% and 67% stealing levels and favorable regions in which type-f customers obtain higher surplus, relative to type-g customers. For $F_p > 1.1$ and $\rho_F(\ell) < 0.265$, the (solid-boxed) isoline for 60% stealing level is inside the region bounded by the dashed-boxed line, that is, the region where type-f customers obtain higher surplus, relative to type-g customers. The corresponding ranges for 67% stealing level, that is, the intersection of the (solid-oval) isoline with the (dashed-oval) favorable region boundary, are $F_p > 0.9$ and $\rho_F(\ell) < 0.34$. 
Optimal Monopolist Distributor Behavior

- Reminder that increasing pursuit investment also increases the number of false positives
Optimal Monopolist Distributor Price, Profits

**FIGURE 7** Optimal (equilibrium) choices of a monopolist distributor: per unit price $p^*$ and $l$ (or, equivalently, $\rho_D(l^*)$) for $\beta = 1.0, 1.5, 2.0, 2.5,$ and $3.0$ and $F = 2.0$.

**FIGURE 8** A monopolist distributor’s optimal profit $\pi_{\ell}^{m^*}(p^*, l^*)$ versus $\rho_D(l^*)$ for $\beta = 1.0, 1.5, 2.0, 2.5,$ and $3.0$ and $F = 2.0$. 
Optimal Distributor Price, Perfect Distributor Competition

• Profits = 0

\[ \pi^c = A + (p - c)q_g(p) + \lambda(-pq_f^S + F\rho D(\ell, q_f^S)) - \psi \ell = 0, \]

• Optimal percentage to steal:

\[ q_f^{st} = \frac{1}{(p^t)^2} (1 - y(p^t, \ell^t)), \]
Comparing Monopoly vs. Competitive Market

• For both, stealing level increases as electricity charge increases (expected)
• For both, stealing level increases as fines imposed decrease (expected)
• Monopolist distributor environments have larger portions of electricity stolen (f-types are going to steal more electricity) as the distributors theft pursuit investment decreases than Competitive distributive environments
• For scenarios where the false alarm rate is limited (and therefore limits theft-pursuit investment)
  – For cases when optimal investment levels are lower, the monopolist distributor chooses a higher electricity price
  – For a given marginal cost of monitoring and fixed fraction of fraudulent customers, the distributor’s equilibrium profit increases with level of investment
Questions?