Single and Multi-Metric Trust Management Frameworks for use in Underwater Autonomous Networks

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Recent Advances of Trust, Security and Privacy in Computing Communications (RATSP)

Summary

- Trust Methods in the MANET space applied to other arenas (e.g. underwater acoustics).
- Trust Management Frameworks (TMFs) require reassessment to work in the harsh marine communications environment.
- Most rely on one type of observation (metric)
- Recent work[1] introduces the use of multiple types of continuous metrics for assessment.

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- Most rely on one type of observation (metric)
- Recent work[1] introduces the use of multiple types of continuous metrics for assessment.
- How do these Single and Multi-Metric Frameworks perform in the challenging marine communications environment?
- What metrics are suitable for use underwater?

Outline

Trust in Conventional MANETS

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- Centralised methods unsuitable for dynamic networks in terms of efficiency and robustness.[2]
- Need to detect, identify, & mitigate threats in a distributed fashion.

Single-Metric TMFs I

Most can be generalised as single-value estimations of PLR/Successful Routes, with the incorporation of some *meta*-observations e.g. Topology

- *Hermes*[3] - Bayesian estimation based on PLR
- *OTMF*[4] - Collaborative Bayesian Trust
- *TSR*[5] - HMM route assessment, Session Loss Rate.
- *CONFIDANT*[6] - Probabilistic PLR assessment, includes topology and reputation weighting.
- *Fuzzy Trust-Based Filtering*[7] - Fuzzy classification of packet delivery

Single-Metric TMFs II

- Opportunities for malicious actors to undermine the operation of a network.
- Not an issue in networks where Comms. is the primary operating concern, but is significant in resource constrained environments

Multi-Metric TMF

Multi-metric Trust For MANETS (MTFM)[1]

- Additional metrics as well as PLR,
- Topological relationship,
- Metric weighting enables behaviour classification
- Grey Relational Grading provides dynamic runtime normalisation, assessing *comparative* trust within a cohort of actors.

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Operates favourably in 802.11 against OTMF and Hermes, accurately detecting, identifying, & characterising misbehaviours.[1]

Multi-Metric TMF - Grey Grading

$$\theta_{k,j}^t = \frac{\min_k |a_{k,j}^t - g_j^t| + \rho \max_k |a_{k,j}^t - g_j^t|}{|a_{k,j}^t - g_j^t| + \rho \max_k |a_{k,j}^t - g_j^t|} \tag{1}$$

$$\phi_{k,j}^t = \frac{\min_k |a_{k,j}^t - b_j^t| + \rho \max_k |a_{k,j}^t - b_j^t|}{|a_{k,j}^t - b_j^t| + \rho \max_k |a_{k,j}^t - b_j^t|} \tag{2}$$

$$[\theta_k^t, \phi_k^t] = \left[\sum_{j=0}^{M} h_j \theta_{k,j}^t, \sum_{j=0}^{M} h_j \phi_{k,j}^t\right] \tag{3}$$

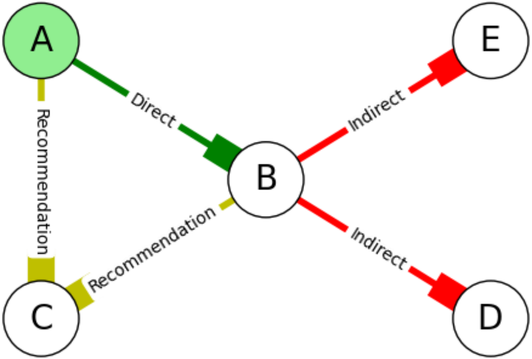
$$T_k^t = (1 + (\phi_k^t)^2/(\theta_k^t)^2)^{-1} \tag{4}$$

Where $a_{k,j}^t$ is the value of an observed metric x_j for a given node k at time t, g and b are respectively the "good" and "bad" reference metric sequences from $\{a_{k,j}^t k = 1, 2 \ldots K\}$, $H = [h_0 \ldots h_M]$ is a metric weighting vector such that $\sum h_j = 1$

Multi-Metric TMF - Topological Relationships

Includes shared assessments from other nodes weighted based on their relative topology to provide a final value[1]

$$T^{MTFM}_{i,j}$$



1 ▸ Details

Outline

Communications Channel Considerations

Key Characteristics of the Marine Acoustic Channel:[8,9,10,11]

- Slow propagation ($1400ms^{-1}$) incurring long delays
- Inter-symbol interference
- Doppler Spreading
- Non-Linear propagation due to refraction
- Fast & Slow fades from environmental factors (flora/fauna/surface and seabed conditions)
- Freq. dependant attenuation
- Significant destructive multipath effects

Attenuation in the Marine Acoustic Channel

The attenuation that occurs in an underwater acoustic channel over distance d about frequency f is given as $A_{aco}(d, f) = A_0 d^k a(f)^d$ or

$$10 \log A_{aco}(d, f)/A_0 = k \cdot 10 \log d + d \cdot 10 \log a(f) \quad (5)$$

where A_0 is a normalising constant, k is a spreading factor, and $a(f)$ is the absorption coefficient;[11]

$$10 \log a(f) = \frac{0.11 \cdot f^2}{1 + f^2} + \frac{44 \cdot f^2}{4100 + f^2} + 2.75 \times 10^{-4} f^2 + 0.003 \quad (6)$$

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Compared to RF Free space PL: ($A_{\mathrm{RF}}(d,f) \approx \left(\frac{4\pi df}{c}\right)^2$)

- Exponential in d: $A_{\mathrm{aco}} \propto f^d$ vs $A_{\mathrm{RF}} \propto (df)^2$
- f factor four orders higher in $f \propto A_{\mathrm{aco}}$ vs $f \propto A_{\mathrm{RF}}$

Operational Considerations: Collaborative AUV Survey

Context:

- Fleets of up to 16 collaborating Autonomous Underwater Vehicles(AUVs)
- Constrained in Power, Mobility, Processing, Storage Capacity
- Tasked to perform ongoing survey of an area

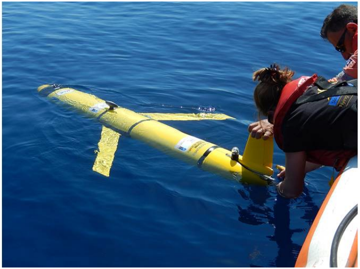

Fig. 1: REMUS 100 AUV as deployed at NATO CMRE La Spezia

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Communications Efficiency is not the only factor at risk from malicious exploitation

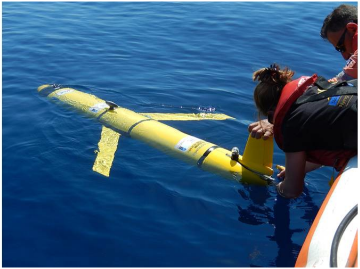

Fig. 1: REMUS 100 AUV as deployed at NATO CMRE La Spezia

Outline

Misbehaviour Specification

- Two misbehaviours investigated:
  - *Malicious Power Control*(MPC) - attacker aims to make a node appear selfish by increasing power to all nodes except to/from it
  - *Selfish Target Selection*(STS) - node preferentially communicates with nodes close to it, to conserve its own power.
- Neither misbehaviour directly affects PLR, while impacting network fairness,
- Default Behaviour: random walk with "Fair" communications
- Three Scenarios:
  - All nodes are Fair
  - One node is Malicious (MPC)
  - One node is Selfish (STS)

Scaling Considerations

- Simulations based on SimPy,[12] Network stack using AUVNetSim[13] and channel constraints based on Stojaovic and Stefanov[10,11] ▸ Details

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- Six per-link communications metrics

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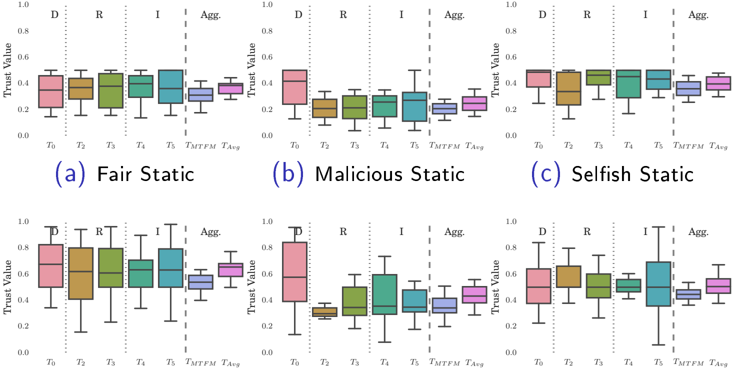
- Received Power
- Received Throughput
- E2E Delay
- Transmitted Power
- Transmitted Throughput
- Packet Loss Rate

Outline

Multi-Metric Operation I



(a) Fair Static (b) Malicious Static (c) Selfish Static

(d) Fair Mobile (e) Malicious Mobile (f) Selfish Mobile

Fig. 2: Observations of n_1 $(T_{1,X})$, showing Direct, Recommender and Indirect relationships and T_{MTFM} and T_{AVG}Y ▸ Closeup

Multi-Metric Operation II

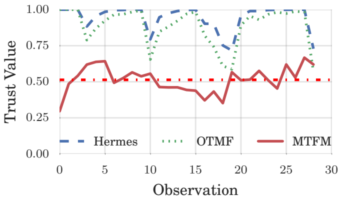
Key Observations:

- Mobility greatly increases variation in observed trust
- T_{MTFM} remains more stable in both mobility cases when compared to either single-node assessments or T_{Avg}
- Raw T_{MTFM} isn't perfect; results demonstrate huge variability in Direct assessment ($T_{1,0}$) that isn't reflected in T_{MTFM}.
- Larger variability in "Fair" case compared to MPC/STS

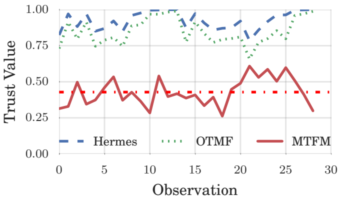
Considering the mobility results and stated context, we continue with mobile-only scenarios.

Outline

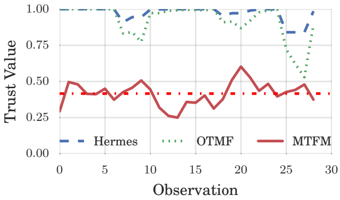
Blind Comparison of Single/Multi-metric TMFs



(a) Fair Scenario



(b) Malicious Power Control Scenario



(c) Selfish Target Selection Scenario

$T_{1,0}$ for Hermes, OTMF and MTFM assessment values for fair and malicious behaviours in the fully mobile scenario (mean of MTFM also shown)

Blind Comparison of Single/Multi-metric TMFs

Key Observations:

- Everybody Sucks

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BUT! MTFM allows exploration of the metric space.

Outline

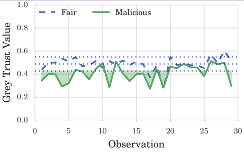
Metric Weighting

From (3), metric emphasise can be adjusted

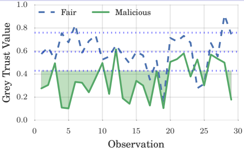
$$[\theta_k^t, \phi_k^t] = \left[\sum_{j=0}^{M} h_j \theta_{k,j}^t, \sum_{j=0}^{M} h_j \phi_{k,j}^t\right] \tag{7}$$

$$T_k^t = (1 + (\phi_k^t)^2 / (\theta_k^t)^2)^{-1} \tag{8}$$

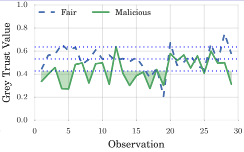
Malicious Power Control - Weighted Emphasis



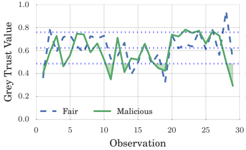
(a) Delay Emphasised



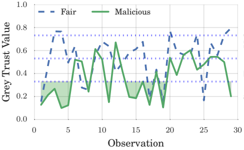
(b) PLR Emphasised



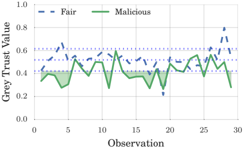
(c) RX Power Emphasised



(d) TX Power Emphasised



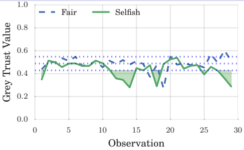
(e) RX Throughput Emphasised



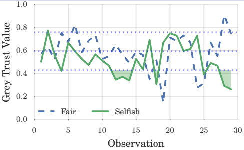
(f) TX Throughput Emphasised

Fig. 3: $T_{1,MTFM}$ in the All Mobile case for the Malicious Power Control behaviour, including dashed $\pm\sigma$ envelope about the fair scenario ▸ Closeup

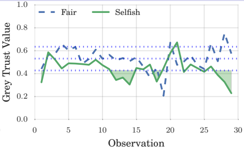
Selfish Target Selection - Weighted Emphasis



(a) Delay Emphasised



(b) PLR Emphasised



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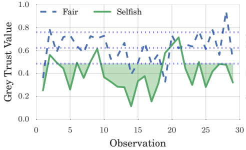
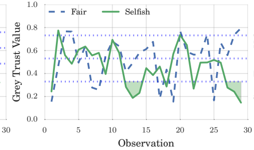


(d) TX Power Emphasised



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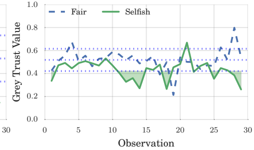

(f) TX Throughput Emphasised

Fig. 4: $T_{1,MTFM}$ in the All Mobile case for the Selfish Target Selection behaviour, including dashed $\pm\sigma$ envelope about the fair scenario ▸ Closeup

Metric Weighting

Key Observations:

- In MPC case:
  - Consistently outside $\pm\sigma$ in most
  - Particularly PLR
  - Less so in Delay, P_{RX} and T_{TX}
- In STS case:
  - Less overall impact
  - Stronger impact of P_{TX}

Outline

Regression of Metric Significance

Aim: Establish which metrics are important in discriminating behaviours

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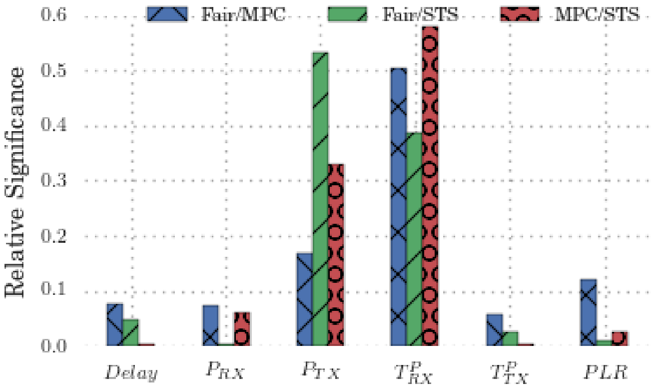
- Distributed Random Forest Regression[14]
- 729 Metric Weight Vectors (H), 512 random trees
- 16 Random starts of each of the 3 scenarios for 6 nodes for 6 hour "missions"
- Targeting area of $\pm\sigma$ deviation $\int abs(T_m - \overline{T}_f) - \sigma_{T_f}$
- Regression identifies the significance of metrics in classifying between the three possible behaviours

Metric Significance



Metric Correlation Combs

Correlation	Delay	P_{RX}	P_{TX}	T^P_{RX}	T^P_{TX}	PLR
Fair / MPC	0.199	0.159	-0.416	0.708	-0.238	-0.401
Fair / STS	0.179	-0.009	0.724	-0.697	-0.145	-0.052
MPC / STS	0.058	-0.134	0.146	-0.768	0.052	0.146

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- MTFM has capability to finely discriminate between similar misbehaviours
- PLR impact is minimal in STS, would not be detected by OTMF/Hermes even in less sparse/harsh environment
- Identifying this classification "comb" is computationally intensive and grows exponentially with number of metrics involved for brute force regression

Summary

- Trust Underwater is Hard, but it's mostly the environments' fault
- Single-Metric Trust is unstable in such an environment
- Multi-Metric Trust works and can discriminate between behaviours
- Not all metrics are equally useful

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- Outlook
  - Extending to include Physical Metrics
  - Developing runtime heuristics to improve complexity
  - Perform untrained classification performance on real data
  - Perform / Initiate practical trials in collaborations with NATO CMRE

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Thank You

Grey Trust Equs I

$$
\begin{aligned}
T_{i,j}^{MTFM} =& \frac{1}{2} \cdot \max_{s}\{f_s(T_{i,j})\}\, T_{i,j} \\
&+ \frac{1}{2} \frac{2|N_R|}{2|N_R| + |N_I|} \sum_{n \in N_R} \max_{s}\{f_s(T_{i,n})\}\, T_{i,n} \\
&+ \frac{1}{2} \frac{|N_I|}{2|N_R| + |N_I|} \sum_{n \in N_I} \max_{s}\{f_s(T_{i,n})\}\, T_{i,n}
\end{aligned} \tag{9}
$$

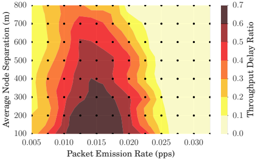
Where $T_{i,n}$ is the subjective trust assessment of n_i by n_n, and $f_s = [f_1, f_2, f_3]$ given as...

Grey Trust Equs II

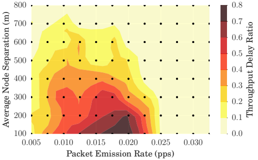
$$
\begin{aligned}
f_1(x) &= -x + 1 \\
f_2(x) &= \begin{cases} 2x & \text{if } x \leq 0.5 \\ -2x + 2 & \text{if } x > 0.5 \end{cases} \\
f_3(x) &= x
\end{aligned}
\tag{10}
$$

Back

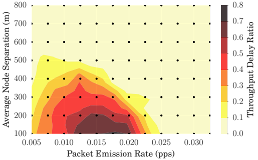
Comms Scaling Graphs I



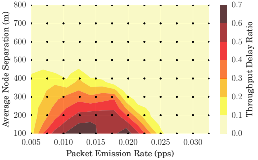
(a) All Nodes Static



(b) n_1 Random Walk



(c) All nodes but n_1 Random Walk



(d) All nodes Random Walk

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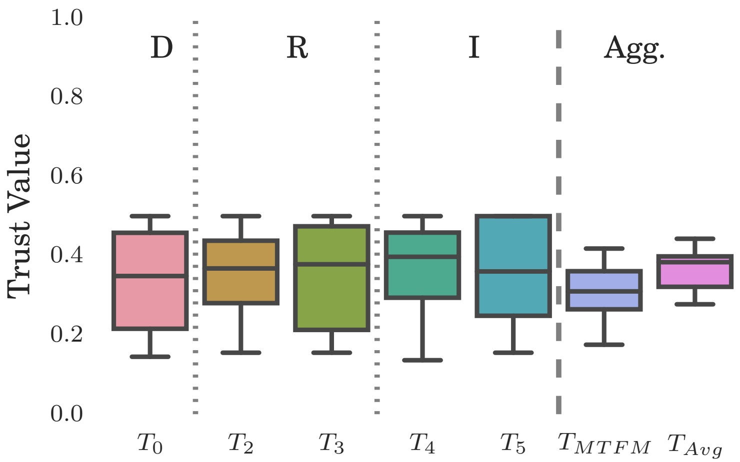
System Model Constraints

Table 1: Comparison of system model constraints as applied between Terrestrial and Marine communications ▸ Back

Parameter	Unit	Terrestrial	Marine
Simulated Duration	s	300	18000
Trust Sampling Period	s	1	600
Simulated Area	km^2	0.7	0.7-4
Transmission Range	km	0.25	1.5
Physical Layer		RF(802.11)	Acoustic
Propagation Speed	m/s	3×10^8	1490
Center Frequency	Hz	2.6×10^9	2×10^4
Bandwidth	Hz	22×10^6	1×10^4
MAC Type		CSMA/DCF	CSMA/CA
Routing Protocol		DSDV	FBR
Max Speed	ms^{-1}	5	1.5
Max Data Rate	bps	5×10^6	≈ 240
Packet Size	bits	4096	9600
Single Transmission Duration	s	10	32
Single Transmission Size	bits	10^7	9600

MTFM Operation Detail



(a) Fair Static

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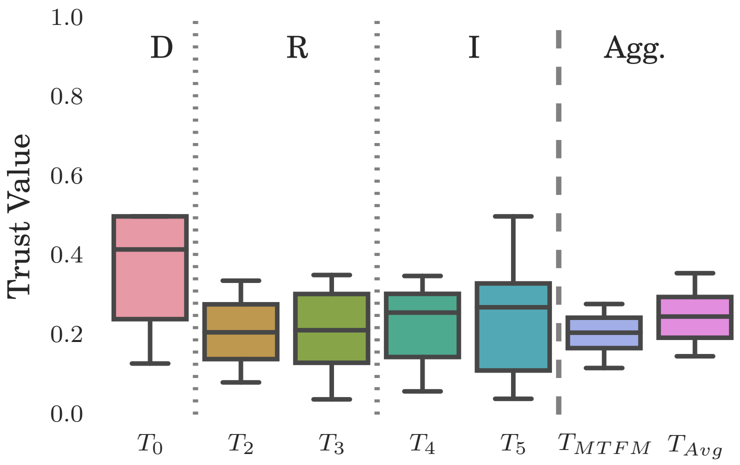
MTFM Operation Detail



(b) Malicious Static

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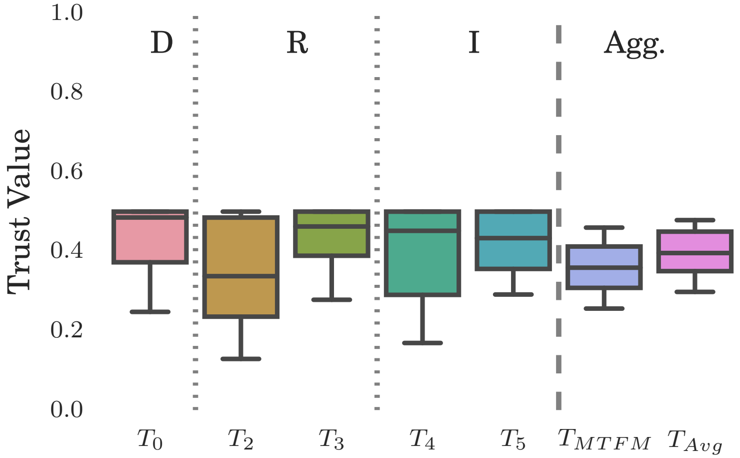
MTFM Operation Detail



(c) Selfish Static

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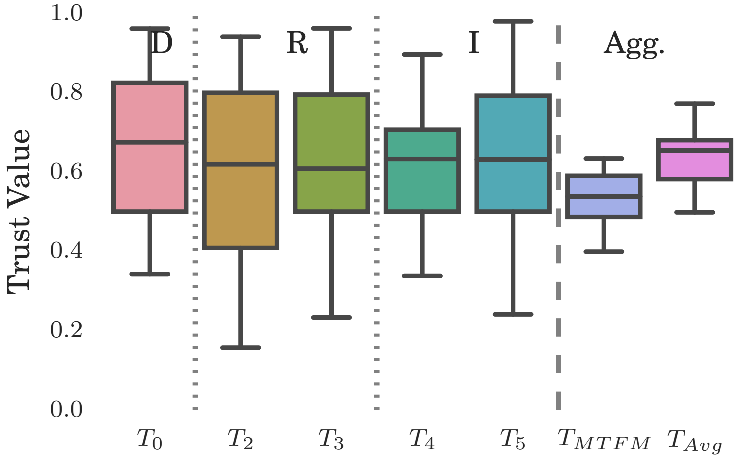
MTFM Operation Detail



(d) Fair Mobile

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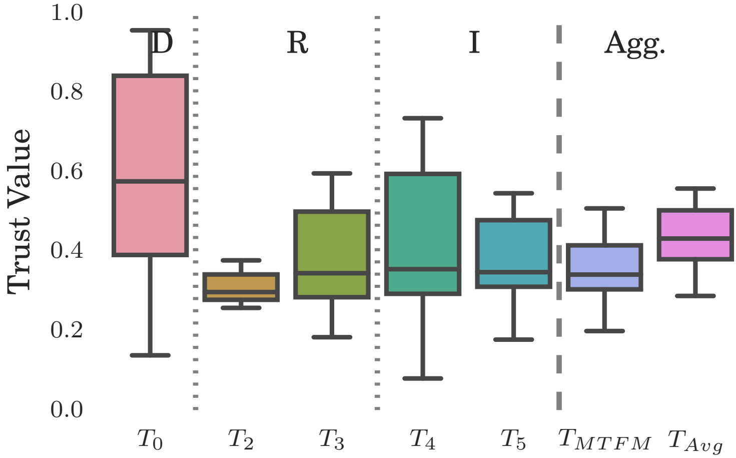
MTFM Operation Detail



(e) Malicious Mobile

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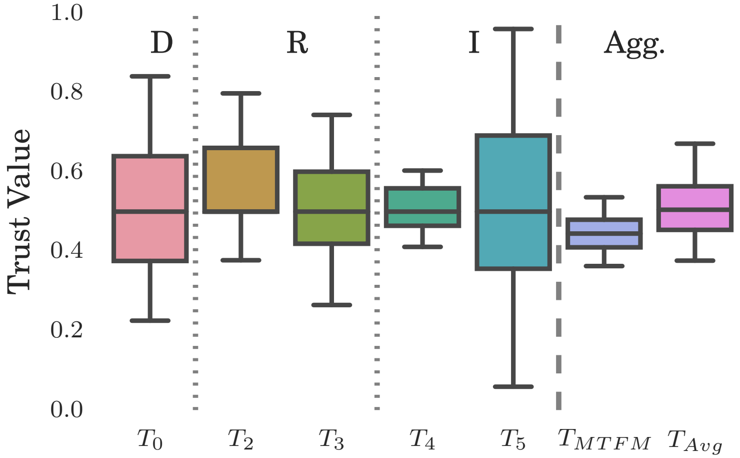
MTFM Operation Detail



(f) Selfish Mobile

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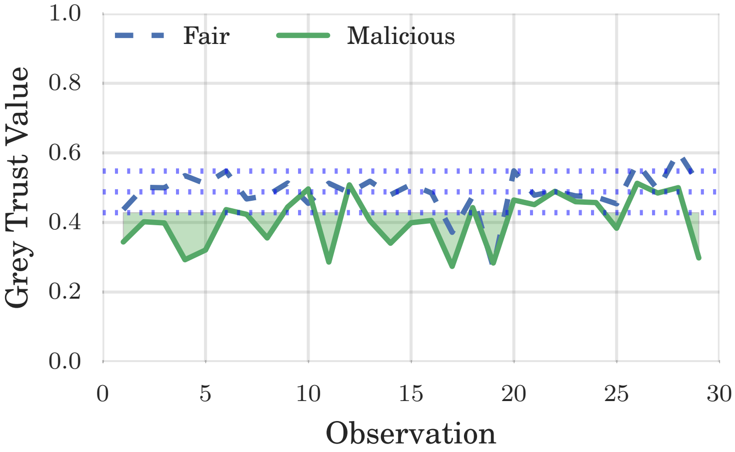
MTFM Malicious Power Control Detail



(a) Delay Emphasised

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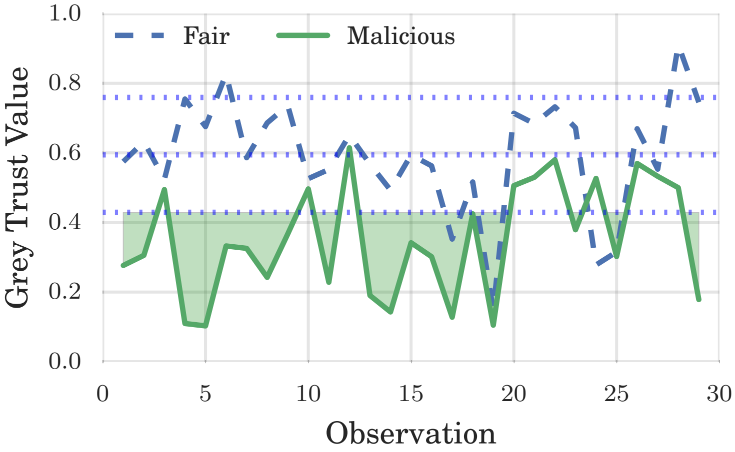
MTFM Malicious Power Control Detail



(b) PLR Emphasised

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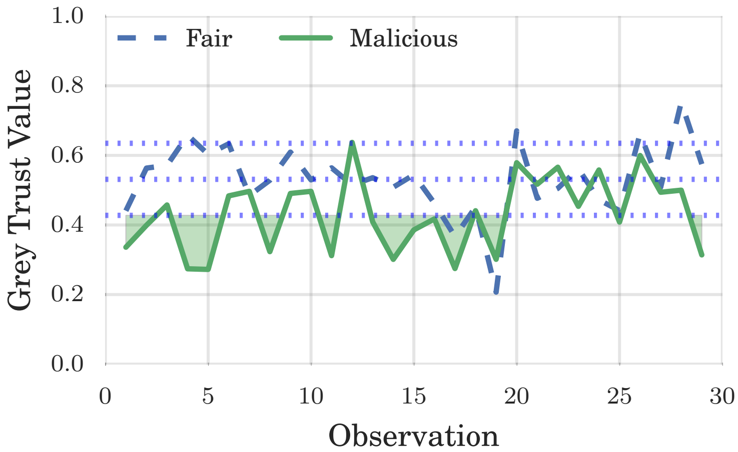
MTFM Malicious Power Control Detail



(c) RX Power Emphasised

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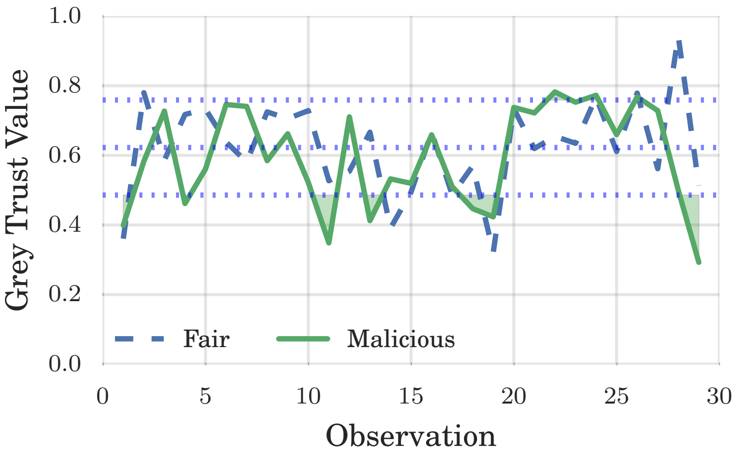
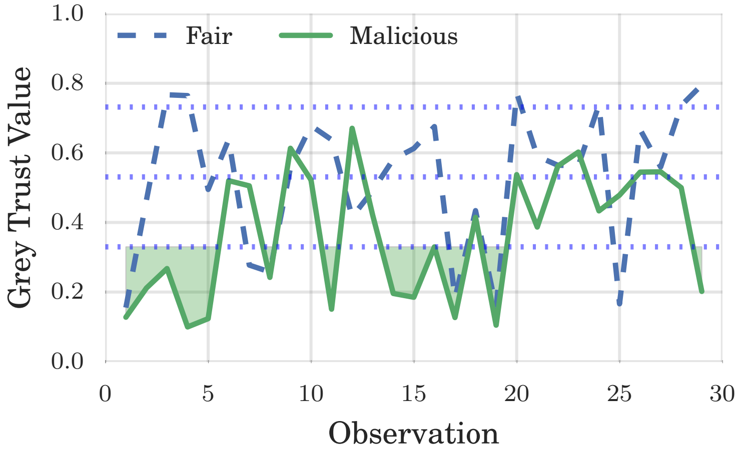
MTFM Malicious Power Control Detail



(d) TX Power Emphasised

MTFM Malicious Power Control Detail



(e) RX Throughput Emphasised

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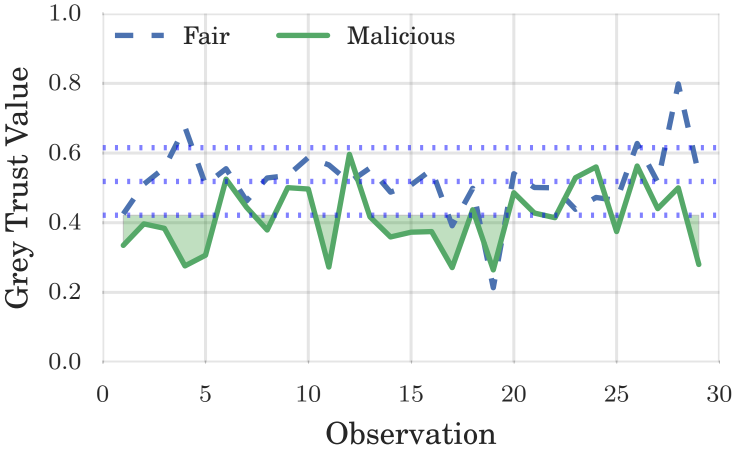
MTFM Malicious Power Control Detail



(f) TX Throughput Emphasised

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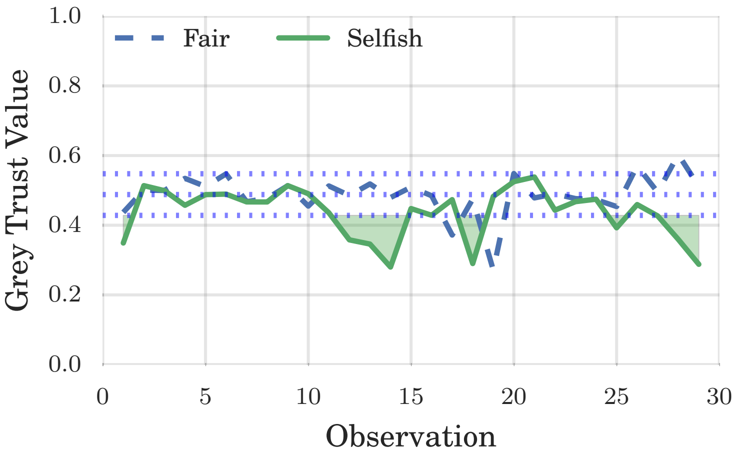
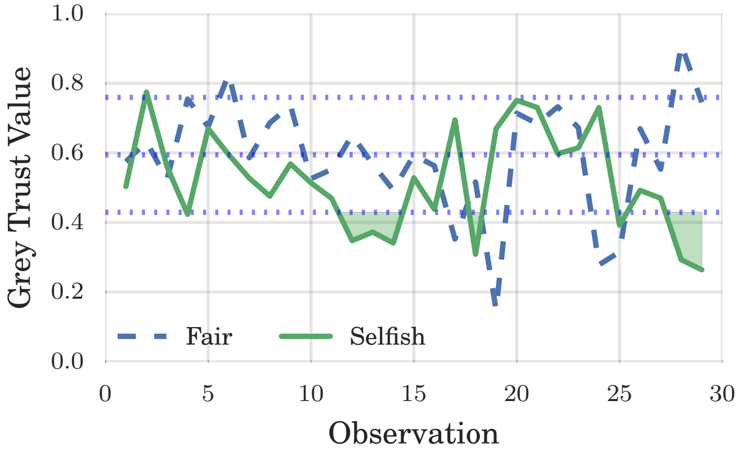
MTFM Selfish Target Selection Detail



(a) Delay Emphasised

▸ Back

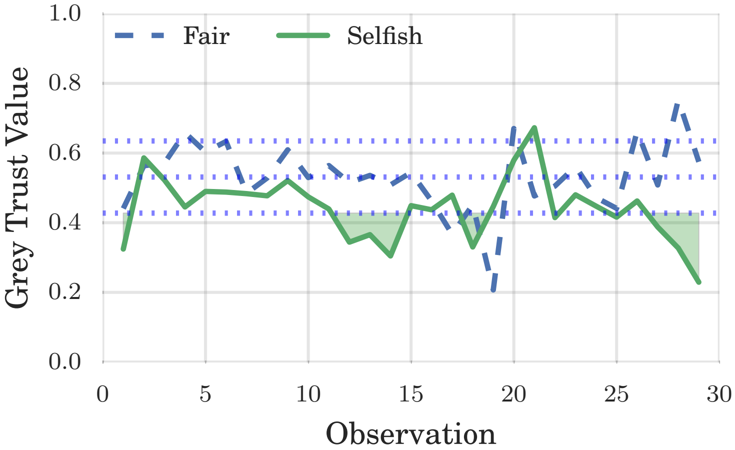
MTFM Selfish Target Selection Detail



(b) PLR Emphasised

Back

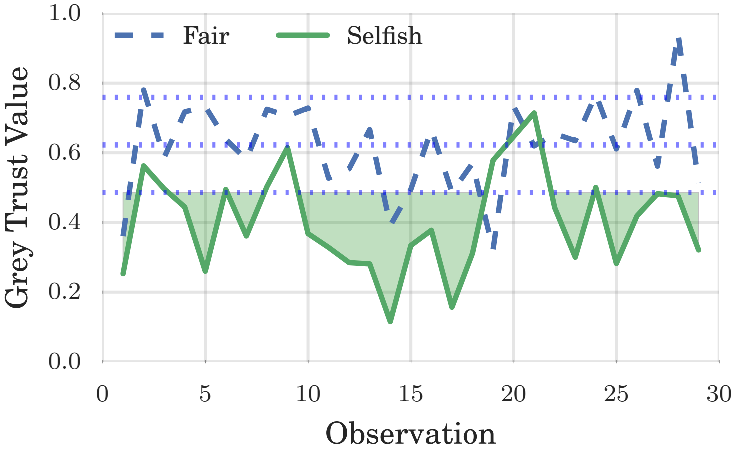
MTFM Selfish Target Selection Detail



(c) RX Power Emphasised

▸ Back

MTFM Selfish Target Selection Detail



(d) TX Power Emphasised

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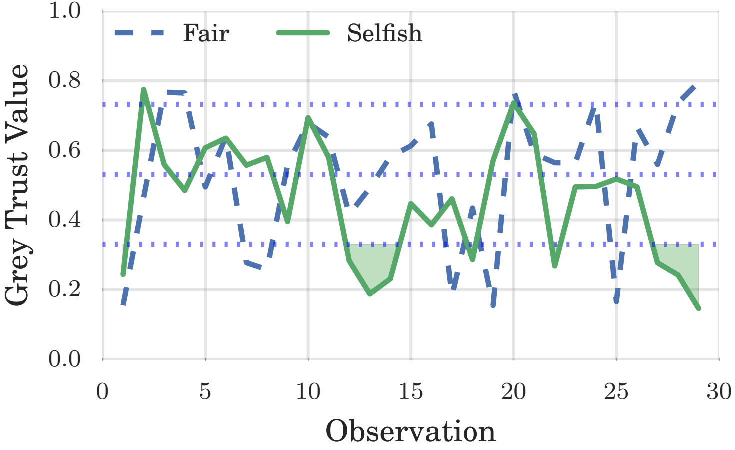
MTFM Selfish Target Selection Detail



(e) RX Throughput Emphasised

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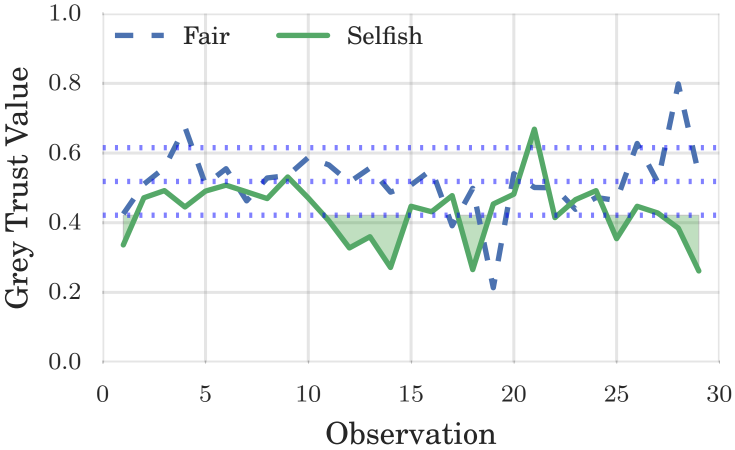
MTFM Selfish Target Selection Detail



(f) TX Throughput Emphasised

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