Max-Min Fairness for IRS-Assisted Secure Two-Way Communications

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***Abstract*—This document describes the most common article elements and how to use the IEEEtran class with LaTeX to produce files that are suitable for submission to the IEEE. IEEEtran can produce conference, journal, and technical note (correspondence) papers with a suitable choice of class options.**

***Index Terms*—Article submission, IEEE, IEEEtran, journal, LaTeX, paper, template, typesetting.**

I. Introduction

Intelligent reflecting surface (IRS)

Notations: Bold symbols in capital letter and small letter denote matrices and vectors, respectively...

$\mathcal{CN}(\mu, \sigma^2)$ denotes the distribution of a *circularly symmetric complex Gaussian* (CSCG) random variable of mean μ and variance σ^2.

Check $\mathbb{C}^{x \times y}$ notation as well

$(a)^+ = max(0, a)$

II. System Model and Problem Formulation

A. System Model

In this paper we consider an IRS assisted two-way communication system as shown in Fig. 1. The communication environment consists of N pairs of legitimate users denoted by $\mathcal{U} \triangleq \{A_i, B_i\}$ for $i = 1, ..., N$, that can be divided into group A and group B. The legitimate users are exposed to an single-antenna eavesdropper E that can overhear the confidential information exchanged between the user pairs. An IRS consisting of L elements is deployed to assist the secure communication. Each legitimate user consist of a single-antenna receiver and a single-antenna transmitter facilitating in-band full-duplex (FD) communication.

It is assumed that the global channel state information (CSI) of the legitimate users and the eavesdropper is available at the centralized system consisting of all the users and the IRS. The control information and the CSI is exchanged using low bandwidth links. CSI estimation is carried out exploiting the channel reciprocity property.

Let $h_{jk} \in \mathbb{C}^{1\times 1}, j = 1, ..., N, k = 1, ..., N$ denote the direct channel from user A_j to user B_k, $\boldsymbol{f}_j \in \mathbb{C}^{L\times 1}$, $j = 1, ..., N$ denote that from the user A_j to the IRS and $\boldsymbol{g}_k \in \mathbb{C}^{L\times 1}$, $k = 1, ..., N$ denote that from the user B_k to the IRS. The direct channels from users A_j and B_k to the eavesdropper E are denoted by $f_{je} \in \mathbb{C}^{1\times 1}$, $j = 1, ..., N$ and $g_{ke} \in \mathbb{C}^{1\times 1}$,

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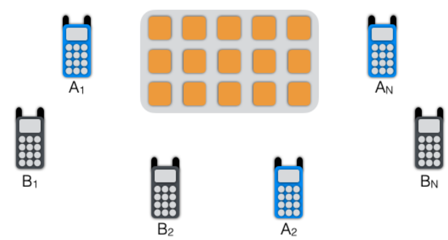

Fig. 1. IRS-Assisted secure multi-pair communication model.(Work in progress)

$k = 1, ..., N$ respectively. The channel from the eavesdropper E to the IRS is denoted by $\boldsymbol{q} \in \mathbb{C}^{L\times 1}$.

Let $\boldsymbol{\omega}^{\dagger}_{ind} = [e^{j\phi_1}, ..., e^{j\phi_L}]$ denote the reflection matrix of the IRS where, $\phi_i \in [0, 2\pi)$ for $i = 1, ..., L$ is the phase shift of the i-th element of the IRS. We have assumed full signal reflection for the ease of practical implementation and maximizing the reflected signal power from the IRS.

The effective channel from the user A_j to user B_k due to direct path and cascaded user-IRS-user channel can be expressed as $\boldsymbol{\omega}^{\dagger}\mathbf{H}_{A_j,B_k}$, where $\boldsymbol{\omega}^{\dagger} = [\boldsymbol{\omega}^{\dagger}_{ind} \;\; 1]$ and $\mathbf{H}^T_{A_j,B_k} = [\boldsymbol{f}^T_j diag(\boldsymbol{g}_k) \;\, h_{jk}] \in \mathbb{C}^{1\times(L+1)}$. Similarly, the effective channel from the user A_j to eavesdropper E can be expressed as $\boldsymbol{\omega}^{\dagger}\mathbf{H}_{A_j,E}$, where $\mathbf{H}^T_{A_j,E} = [\boldsymbol{f}^T_j diag(\boldsymbol{q}) \;\, f_{je}] \in \mathbb{C}^{1\times(L+1)}$. The information symbol and power transmitted by the user A_j can be denoted as $s_{A_j} \in \mathcal{CN}(0, 1)$ and P_{A_j} respectively. Let $\mathbf{P} = [P_{A_1}, P_{B_1}, ..., P_{A_N}, P_{B_N}]$ denote all the transmit powers of legitimate users.

Without loss of generality, the received signal at the arbitrary user A_j from group A can be expressed as

$$\begin{aligned} y_{A_j} = & \underbrace{\sqrt{P_{A_j}}\boldsymbol{\omega}^{\dagger}\mathbf{H}_{A_j,A_j}s_{A_j}}_{\text{Self interference}} + \underbrace{\sum_{\substack{i=1\\ i\neq j}}^{N}\sqrt{P_{A_i}}\boldsymbol{\omega}^{\dagger}\mathbf{H}_{A_i,A_j}s_{A_i}}_{\text{Inter-pair interference}} \\ & + \underbrace{\sqrt{P_{B_j}}\boldsymbol{\omega}^{\dagger}\mathbf{H}_{B_j,A_j}s_{B_j}}_{\text{Desired signal}} + \underbrace{\sum_{\substack{i=1\\ i\neq j}}^{N}\sqrt{P_{B_i}}\boldsymbol{\omega}^{\dagger}\mathbf{H}_{B_i,A_j}s_{B_i}}_{\text{Inter-pair interference}} \qquad (1) \\ & + \underbrace{n_{A_j} + l_{A_j}}_{\text{Noise and loop interference}}, \end{aligned}$$

where $n_{A_j} \in \mathcal{N}(0, \sigma^2)$ is additive white Gaussian noise (AWGN) at A_j. The residual loop-interference after the FD-

$$R_{A_j}^{B_j} = log_2\left(1 + \frac{P_{B_j}|\boldsymbol{\omega}^\dagger \mathbf{H}_{B_j,A_j}|^2}{\sum_{\substack{i=1\\i\neq j}}^{N}\left(P_{A_i}|\boldsymbol{\omega}^\dagger \mathbf{H}_{A_i,A_j}|^2 + P_{B_i}|\boldsymbol{\omega}^\dagger \mathbf{H}_{B_i,A_j}|^2\right) + \sigma^2 + \sigma_l^2}\right) \tag{2}$$

$$R_{E}^{B_j} = log_2\left(1 + \frac{P_{B_j}|\boldsymbol{\omega}^\dagger \mathbf{H}_{B_j,E}|^2}{\sum_{i=1}^{N} P_{A_i}|\boldsymbol{\omega}^\dagger \mathbf{H}_{A_i,E}|^2 + \sum_{\substack{i=1\\i\neq j}}^{N} P_{B_i}|\boldsymbol{\omega}^\dagger \mathbf{H}_{B_i,E}|^2 + \sigma^2}\right) \tag{3}$$

operation at A_j is denoted by l_{A_j}, which is assumed to be a random variable of zero mean and variance σ_l^2. Since the global CSI is available at all the users, the self-interference term is assumed to be completely suppressed at the user A_j.

Assuming the eavesdropper E is wiretapping the signal emitted by user A_j, the received signal at the eavesdropper E can be expressed as

$$\begin{aligned} y_E = &\underbrace{\sum_{i=1}^{N}\sqrt{P_{A_i}}\boldsymbol{\omega}^\dagger \mathbf{H}_{A_i,E}s_{A_i} + \sum_{\substack{i=1\\i\neq j}}^{N}\sqrt{P_{B_i}}\boldsymbol{\omega}^\dagger \mathbf{H}_{B_i,E}s_{B_i}}_{\text{Interference}} \\ &+ \underbrace{\sqrt{P_{B_j}}\boldsymbol{\omega}^\dagger \mathbf{H}_{B_j,E}s_{B_j}}_{\text{Signal of interest}} + \underbrace{n_E}_{\text{Noise}}, \end{aligned} \tag{4}$$

where $n_E \in \mathcal{N}(0, \sigma^2)$ is additive white Gaussian noise (AWGN) at E.

According to (1), the achievable transmission rate confidential message received at user A_j can be expressed as (2). According to (4), if the eavesdropper E attempts to eavesdrop the signal from A_j, the achievable wiretapped rate at E can be expressed as (3). The individual secrecy-rate achieved by the user A_j can be written as

$$C_{A_j} = \left[R_{A_j}^{B_j} - R_{E}^{B_j}\right]^+. \tag{5}$$

A similar expression can be obtained for an arbitrary user B_j from group B.

B. Problem Formulation

In this paper we maximize the minimum secrecy-rate among all the legitimate users $\mathcal{U}$ to achieve fairness by jointly optimizing the IRS reflection matrix $\boldsymbol{\omega}$ and the transmit powers $\mathbf{P}$. The optimization problem is constrained by minimum and maximum individual transmit power constraints of the legitimate users. The optimization problem can be formulated as

$$\begin{aligned} \text{(P1):} \quad & \max_{\boldsymbol{\omega},\mathbf{P}} \min_{X\in\mathcal{U}} \quad C_X && \text{(6a)}\\ & \text{s.t.} \quad |\omega^{(j)}| = 1 \qquad \forall 1 \le j \le L, && \text{(6b)}\\ & \qquad \omega^{(L+1)} = 1, && \text{(6c)}\\ & \qquad P_{\min} \le P_X \le P_{\max} \qquad \forall X \in \mathcal{U}. && \text{(6d)} \end{aligned}$$

The j-th element of the vector $\boldsymbol{\omega}$ is denoted by $\omega^{(j)}$. The constraint (6b) ensures that only the phase of the signal is altered by the IRS elements without affecting the magnitude. The constraint (6d) ensures that the transmit power at each user is bounded by maximum and minimum feasible power thresholds $P_{\max}$ and $P_{\min}$ respectively.

The optimization problem (6) is non-convex due to non-concave objective function (6a) and non-convex constraint (6b). The optimization variables $\mathbf{P}$ and $\boldsymbol{\omega}$ are coupled in the objective function, which makes the problem non-convex in both variables at once. There is no standard technique to solve this problem optimally. We proceed with an iterative algorithm to solve this problem efficiently.

III. Minimum Secrecy Rate Maximization

In this section, we transform the problem (P1) into a tractable form and employ alternating optimization (AO) technique.

A. Problem transformation

Similar to the work in [1], problem (P1) can be converted to its equivalent epigraph problem (P2) by introducing an auxiliary variable t. In order to relax the non-convex constraint (6c) we obtain $\tilde{\boldsymbol{\omega}}$ from $\boldsymbol{\omega}$ by multiplying each element with complex number ν satisfying $|\nu| = 1$.

$$\tilde{\boldsymbol{\omega}} = \nu\boldsymbol{\omega} = \begin{bmatrix}\nu\boldsymbol{\omega}_{ind}\\ \nu\end{bmatrix} \tag{7}$$

Problem (P1) is then converted to a semi-definite relaxation (SDR) problem by the employing the substitution $|\boldsymbol{\omega}^\dagger \mathbf{H}_{X,Y}|^2 = \text{Tr}(\tilde{\mathbf{H}}_{X,Y}\boldsymbol{W})$, $X, Y \in \mathcal{U}$, where $\tilde{\mathbf{H}}_{X,Y} = \mathbf{H}_{X,Y}\mathbf{H}_{X,Y}^\dagger$ and $\boldsymbol{W} = \tilde{\boldsymbol{\omega}}\tilde{\boldsymbol{\omega}}^\dagger$. Similar to (5), which can be updated by substituting (2) and (3), all the constraints (8b) in the transformed optimization problem (P2) can be updated.

$$\begin{aligned} \text{(P2):} \quad & \max_{\boldsymbol{W},\mathbf{P}} \quad t && \text{(8a)}\\ & \text{s.t.} \quad C_X \ge t \qquad \forall X \in \mathcal{U}, && \text{(8b)}\\ & \qquad \text{diag}(\boldsymbol{W}) = 1 && \text{(8c)}\\ & \qquad \boldsymbol{W} \succeq 0, && \text{(8d)}\\ & \qquad \text{Rank}(\boldsymbol{W}) = 1, && \text{(8e)}\\ & \qquad P_{\min} \le P_X \le P_{\max} \qquad \forall X \in \mathcal{U}. && \text{(8f)} \end{aligned}$$

Mention the Rank-1 issue as well. We relax the non-convex Rank-1 constraint for solving the problem. It is not guaranteed that the final solution will necessarily be Rank-1.

Write down the long form of difference of two convex functions of P and W.

$$P_{A_j} = log_2\left(\sum_{\substack{i=1\\i\neq j}}^{N} P_{A_i}\mathrm{Tr}(\mathbf{H}_{A_i,A_j}\boldsymbol{W}) + \sum_{i=1}^{N} P_{B_i}\mathrm{Tr}(\mathbf{H}_{B_i,A_j}\boldsymbol{W}) + \sigma^2 + \sigma_l^2\right) + log_2\left(\sum_{i=1}^{N} P_{A_i}\mathrm{Tr}(\mathbf{H}_{A_i,E}\boldsymbol{W}) + \sum_{\substack{i=1\\i\neq j}}^{N} P_{B_i}\mathrm{Tr}(\mathbf{H}_{B_i,E}\boldsymbol{W}) + \sigma^2\right) \quad (9)$$

$$Q_{A_j} = log_2\left(\sum_{\substack{i=1\\i\neq j}}^{N} \left[P_{A_i}\mathrm{Tr}(\mathbf{H}_{A_i,A_j}\boldsymbol{W}) + P_{B_i}\mathrm{Tr}(\mathbf{H}_{B_i,A_j}\boldsymbol{W})\right] + \sigma^2 + \sigma_l^2\right) + log_2\left(\sum_{i=1}^{N} P_{A_i}\mathrm{Tr}(\mathbf{H}_{A_i,E}\boldsymbol{W}) + \sum_{\substack{i=1\\i\neq j}}^{N} P_{B_i}\mathrm{Tr}(\mathbf{H}_{B_i,E}\boldsymbol{W}) + \sigma^2\right) \quad (10)$$

Still the problem is non-convex due to coupled optimization variables and the non-convex nature of the constraints (8b). We use Taylor approximation to convert each constraint into a convex lower bound. Then alternative optimization (AO) technique is used to optimize power variable P and IRS phases W in an alternating manner.

B. Transmit power optimization

test

C. IRS phase optimization

test

Temporary notes - Problem Solving

- Introduction of auxiliary variable t
- Preparation of reflection matrix for SDP (Semi-definite programming) (Mention the other papers)
- P and W are coupled in a way that makes the problem non-convex
- Introduce what we do by employing alternating optimization (AO)
- Introduce Taylor approximation
- Introduce successive convex approximation
- Introduce Gaussian randomization
- Introduce suitable substitutions
- Make sure the steps are not too long or not too short

Temporary notes - Related works

- Mention papers that use bisection based techniques for max-min
- Mention several other multiuser IRS papers that employ max-min
- Mention the relay-assisted two-way communication papers

Temporary notes - Problem formulation

- Describe what each of these constraints mean physically
- Give sub-indexing to constraints
- The objective function is non-concave
- mention what constraints are non-concave
- No standard way to optimally solve
- As a solution you need to transform the problem
- Mention that an AO(Alternating Optimization) algorithm is proposed.
- Some papers give descriptive explanations of AO algorithms.

Temporary notes - System model

- Introduce channels, IRS phase matrix
- Talk about information symbol
- Power of transmitters
- Number of pairs.
- Finding a smart way to represent channels.
- Mention about the eavesdropper as well.
- Add the channel from eavesdropper to the IRS and users
- Mention the received channel at a arbitrary user and the eavesdropper.
- Assumption 1: Two-way communications: Self Interference and Loop Interference can be suppressed completely. Residual loop interference is left.
- Assumption 2: Full signal reflection at each signal reflection. For the ease of practical implementation and maximizing reflected power.
- Assumption 3: How the IRS Tx Rx are connected. Where is the CPU.: CPU is connected to all the users as well as the IRS using a different allocated bandwidth for sharing the overhead.
- Assumption 4: Talking about the CSI: Availability of full CSI to all the users including the CSI of the eavesdropper in the CPU. Use of channel reciprocity for CSI acquisition.
- Mention the received channel at a arbitrary user and the eavesdropper.
- Introduce the secrecy rate; Introduce the transmission rates; next introduce the secrecy rate formula using transmission rates;
- Finally go for a problem formulation.

IV. Numerical Results

Include charts
With explanations

V. Conclusion

Ending with a good conclusion. If possible appendix is required.

VI. Introduction-old

THIS file is intended to serve as a "sample article file" for IEEE journal papers produced under LaTeX using IEEEtran.cls version 1.8b and later. The most common elements are covered in the simplified and updated instructions in "New_IEEEtran_how-to.pdf". For less common elements you can refer back to the original "IEEEtran_HOWTO.pdf". It is assumed that the reader has a basic working knowledge of LaTeX. Those who are new to LaTeX are encouraged to read Tobias Oetiker's "The Not So Short Introduction to LaTeX," available at: http://tug.ctan.org/info/lshort/english/lshort.pdf which provides an overview of working with LaTeX.

VII. The Design, Intent, and Limitations of the Templates

The templates are intended to **approximate the final look and page length of the articles/papers**. **They are NOT intended to be the final produced work that is displayed in print or on IEEEXplore®**. They will help to give the authors an approximation of the number of pages that will be in the final version. The structure of the LaTeX files, as designed, enable easy conversion to XML for the composition systems used by the IEEE. The XML files are used to produce the final print/IEEEXplore pdf and then converted to HTML for IEEEXplore.

VIII. Where to Get LaTeX Help — User Groups

The following online groups are helpful to beginning and experienced LaTeX users. A search through their archives can provide many answers to common questions.

http://www.latex-community.org/
https://tex.stackexchange.com/

IX. Other Resources

See [**?**], [**?**], [**?**], [**?**], [**?**] for resources on formatting math into text and additional help in working with LaTeX.

X. Text

For some of the remainer of this sample we will use dummy text to fill out paragraphs rather than use live text that may violate a copyright.

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$$x = \sum_{i=0}^{n} 2iQ. \tag{11}$$

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XI. Some Common Elements

A. *Sections and Subsections*

Enumeration of section headings is desirable, but not required. When numbered, please be consistent throughout the article, that is, all headings and all levels of section headings in the article should be enumerated. Primary headings are designated with Roman numerals, secondary with capital letters, tertiary with Arabic numbers; and quaternary with lowercase letters. Reference and Acknowledgment headings are unlike all other section headings in text. They are never enumerated. They are simply primary headings without labels, regardless of whether the other headings in the article are enumerated.

B. *Citations to the Bibliography*

The coding for the citations is made with the LaTeX `\cite` command. This will display as: see [3].

Fig. 2. Simulation results for the network.

For multiple citations code as follows: `\cite{ref1,ref2,ref3}` which will produce [3]. For reference ranges that are not consecutive code as `\cite{ref1,ref2,ref3,ref9}` which will produce [**?**], [**?**], [**?**], [**?**]

C. Lists

In this section, we will consider three types of lists: simple unnumbered, numbered, and bulleted. There have been many options added to IEEEtran to enhance the creation of lists. If your lists are more complex than those shown below, please refer to the original "IEEEtran_HOWTO.pdf" for additional options.

A plain unnumbered list:

bare_jrnl.tex
bare_conf.tex
bare_jrnl_compsoc.tex
bare_conf_compsoc.tex
bare_jrnl_comsoc.tex

A simple numbered list:

1) bare_jrnl.tex
2) bare_conf.tex
3) bare_jrnl_compsoc.tex
4) bare_conf_compsoc.tex
5) bare_jrnl_comsoc.tex

A simple bulleted list:

- bare_jrnl.tex
- bare_conf.tex
- bare_jrnl_compsoc.tex
- bare_conf_compsoc.tex
- bare_jrnl_comsoc.tex

D. Figures

Fig. 1 is an example of a floating figure using the graphicx package. Note that `\label` must occur AFTER (or within) `\caption`. For figures, `\caption` should occur after the `\includegraphics`.

TABLE I
AN EXAMPLE OF A TABLE

One	Two
Three	Four

Fig. 2(a) and 2(b) is an example of a double column floating figure using two subfigures. (The subfig.sty package must be loaded for this to work.) The subfigure `\label` commands are set within each subfloat command, and the `\label` for the overall figure must come after `\caption`. `\hfil` is used as a separator to get equal spacing. The combined width of all the parts of the figure should do not exceed the text width or a line break will occur.

Note that often IEEE papers with multi-part figures do not place the labels within the image itself (using the optional argument to `\subfloat`[]), but instead will reference/describe all of them (a), (b), etc., within the main caption. Be aware that for subfig.sty to generate the (a), (b), etc., subfigure labels, the optional argument to `\subfloat` must be present. If a subcaption is not desired, leave its contents blank, e.g.,`\subfloat`[].

XII. TABLES

Note that, for IEEE-style tables, the `\caption` command should come BEFORE the table. Table captions use title case. Articles (a, an, the), coordinating conjunctions (and, but, for, or, nor), and most short prepositions are lowercase unless they are the first or last word. Table text will default to `\footnotesize` as the IEEE normally uses this smaller font for tables. The `\label` must come after `\caption` as always.

XIII. ALGORITHMS

Algorithms should be numbered and include a short title. They are set off from the text with rules above and below the title and after the last line.

Algorithm 1 Weighted Tanimoto ELM.

TRAIN($\mathbf{XT}$)
 select randomly $W \subset \mathbf{X}$
 $N_{\mathbf{t}} \leftarrow |\{i : \mathbf{t}_i = \mathbf{t}\}|$ **for** $\mathbf{t} = -1, +1$
 $B_i \leftarrow \sqrt{\textsc{max}(N_{-1}, N_{+1})/N_{\mathbf{t}_i}}$ **for** $i = 1, ..., N$
 $\hat{\mathbf{H}} \leftarrow B \cdot (\mathbf{X}^T\mathbf{W})/(\mathbb{1}\mathbf{X} + \mathbb{1}\mathbf{W} - \mathbf{X}^T\mathbf{W})$
 $\beta \leftarrow \left(I/C + \hat{\mathbf{H}}^T\hat{\mathbf{H}}\right)^{-1}(\hat{\mathbf{H}}^T B \cdot \mathbf{T})$
 return $\mathbf{W}, \beta$

PREDICT($\mathbf{X}$)
 $\mathbf{H} \leftarrow (\mathbf{X}^T\mathbf{W})/(\mathbb{1}\mathbf{X} + \mathbb{1}\mathbf{W} - \mathbf{X}^T\mathbf{W})$
 return $\textsc{sign}(\mathbf{H}\beta)$

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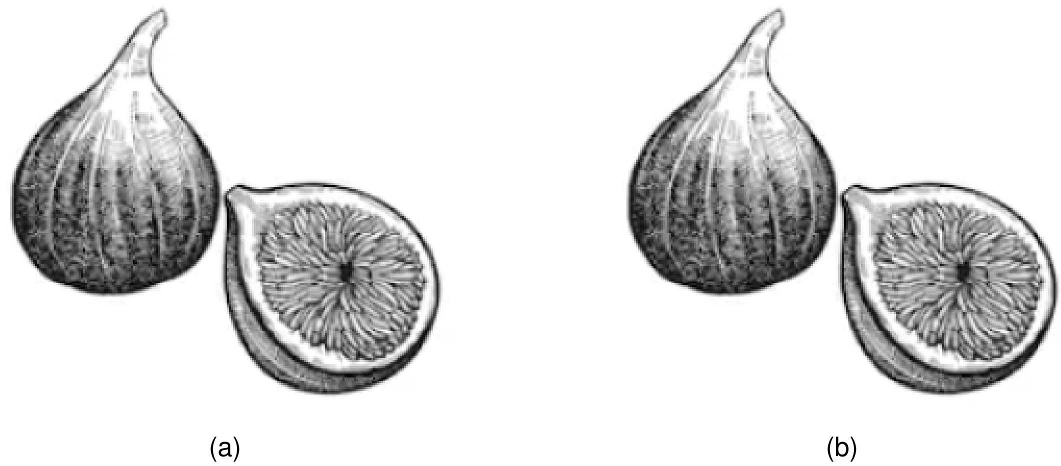

Fig. 3. Dae. Ad quatur autat ut porepel itemoles dolor autem fuga. Bus quia con nessunti as remo di quatus non perum que nimus. (a) Case I. (b) Case II.

XIV. Mathematical Typography and Why It Matters

Typographical conventions for mathematical formulas have been developed to **provide uniformity and clarity of presentation across mathematical texts**. This enables the readers of those texts to both understand the author's ideas and to grasp new concepts quickly. While software such as LaTeX and MathType® can produce aesthetically pleasing math when used properly, it is also very easy to misuse the software, potentially resulting in incorrect math display.

IEEE aims to provide authors with the proper guidance on mathematical typesetting style and assist them in writing the best possible article. As such, IEEE has assembled a set of examples of good and bad mathematical typesetting [**?**], [**?**], [**?**], [**?**], [**?**].

Further examples can be found at http://journals.ieeeauthorcenter.ieee.org/wp-content/uploads/sites/7/IEEE-Math-Typesetting-Guide-for-LaTeX-Users.pdf

A. Display Equations

The simple display equation example shown below uses the "equation" environment. To number the equations, use the `\label` macro to create an identifier for the equation. LaTeX will automatically number the equation for you.

$$x = \sum_{i=0}^{n} 2iQ. \tag{12}$$

is coded as follows:

```
\begin{equation}
\label{deqn_ex1}
x = \sum_{i=0}^{n} 2{i} Q.
\end{equation}
```

To reference this equation in the text use the `\ref` macro. Please see (12)
is coded as follows:

```
Please see (\ref{deqn_ex1})
```

B. Equation Numbering

Consecutive Numbering: Equations within an article are numbered consecutively from the beginning of the article to the end, i.e., (1), (2), (3), (4), (5), etc. Do not use roman numerals or section numbers for equation numbering.
Appendix Equations: The continuation of consecutively numbered equations is best in the Appendix, but numbering as (A1), (A2), etc., is permissible.

Hyphens and Periods: Hyphens and periods should not be used in equation numbers, i.e., use (1a) rather than (1-a) and (2a) rather than (2.a) for subequations. This should be consistent throughout the article.

C. Multi-Line Equations and Alignment

Here we show several examples of multi-line equations and proper alignments.
A single equation that must break over multiple lines due to length with no specific alignment.

$$\begin{multline}\text{The first line of this example}\\ \text{The second line of this example}\\ \text{The third line of this example}\tag{13}\end{multline}$$

is coded as:

```
\begin{multline}
\text{The first line of this example}\\
\text{The second line of this example}\\
\text{The third line of this example}
\end{multline}
```

A single equation with multiple lines aligned at the = signs

$$a = c + d \tag{14}$$
$$b = e + f \tag{15}$$

is coded as:

```
\begin{align}
```

```
a &= c+d \\
b &= e+f
\end{align}
```

The align environment can align on multiple points as shown in the following example:

$$
\begin{align}
x &= y & X &= Y & a &= bc \tag{16}\\
x' &= y' & X' &= Y' & a' &= bz \tag{17}
\end{align}
$$

is coded as:

```
\begin{align}
x &= y & X & =Y & a &=bc\\
x' &= y' & X' &=Y' &a' &=bz
\end{align}
```

D. Subnumbering

The amsmath package provides a subequations environment to facilitate subnumbering. An example:

$$
\begin{align}
f &= g \tag{18a}\\
f' &= g' \tag{18b}\\
\mathcal{L}f &= \mathcal{L}g \tag{18c}
\end{align}
$$

is coded as:

```
\begin{subequations}\label{eq:2}
\begin{align}
f&=g \label{eq:2A}\\
f' &=g' \label{eq:2B}\\
\mathcal{L}f &= \mathcal{L}g \label{eq:2c}
\end{align}
\end{subequations}
```

E. Matrices

There are several useful matrix environments that can save you some keystrokes. See the example coding below and the output.

A simple matrix:

$$
\begin{matrix} 0 & 1 \\ 1 & 0 \end{matrix} \tag{19}
$$

is coded as:

```
\begin{equation}
\begin{matrix}  0 &  1 \\
1 &  0 \end{matrix}
\end{equation}
```

A matrix with parenthesis

$$
\begin{pmatrix} 0 & -i \\ i & 0 \end{pmatrix} \tag{20}
$$

is coded as:

```
\begin{equation}
\begin{pmatrix} 0 & -i \\
 i &  0 \end{pmatrix}
\end{equation}
```

A matrix with square brackets

$$
\begin{bmatrix} 0 & -1 \\ 1 & 0 \end{bmatrix} \tag{21}
$$

is coded as:

```
\begin{equation}
\begin{bmatrix} 0 & -1 \\
1 &  0 \end{bmatrix}
\end{equation}
```

A matrix with curly braces

$$
\begin{Bmatrix} 1 & 0 \\ 0 & -1 \end{Bmatrix} \tag{22}
$$

is coded as:

```
\begin{equation}
\begin{Bmatrix} 1 &  0 \\
0 & -1 \end{Bmatrix}
\end{equation}
```

A matrix with single verticals

$$
\begin{vmatrix} a & b \\ c & d \end{vmatrix} \tag{23}
$$

is coded as:

```
\begin{equation}
\begin{vmatrix} a &  b \\
c &  d \end{vmatrix}
\end{equation}
```

A matrix with double verticals

$$
\begin{Vmatrix} i & 0 \\ 0 & -i \end{Vmatrix} \tag{24}
$$

is coded as:

```
\begin{equation}
\begin{Vmatrix} i &  0 \\
0 & -i \end{Vmatrix}
\end{equation}
```

F. Arrays

The array environment allows you some options for matrix-like equations. You will have to manually key the fences, but there are other options for alignment of the columns and for setting horizontal and vertical rules. The argument to array controls alignment and placement of vertical rules.

A simple array

$$
\left(
\begin{array}{cccc}
a+b+c & uv & x-y & 27\\
a+b & u+v & z & 134
\end{array} \right) \tag{25}
$$

is coded as:

```
\begin{equation}
\left(
\begin{array}{cccc}
a+b+c & uv & x-y & 27\\
a+b & u+v & z & 134
\end{array} \right)
```

```
\end{equation}
```

A slight variation on this to better align the numbers in the last column

$$\left(\begin{array}{cccr} a+b+c & uv & x-y & 27\\ a+b & u+v & z & 134 \end{array}\right) \tag{26}$$

is coded as:

```
\begin{equation}
\left(
\begin{array}{cccr}
a+b+c & uv & x-y & 27\\
a+b & u+v & z & 134
\end{array} \right)
\end{equation}
```

An array with vertical and horizontal rules

$$\left(\begin{array}{c|c|c|r} a+b+c & uv & x-y & 27\\ \hline a+b & u+v & z & 134 \end{array}\right) \tag{27}$$

is coded as:

```
\begin{equation}
\left(
\begin{array}{c|c|c|r}
a+b+c & uv & x-y & 27\\
a+b & u+v & z & 134
\end{array} \right)
\end{equation}
```

Note the argument now has the pipe "|" included to indicate the placement of the vertical rules.

G. Cases Structures

Many times cases can be miscoded using the wrong environment, i.e., `array`. Using the `cases` environment will save keystrokes (from not having to type the `\left\lbrace`) and automatically provide the correct column alignment.

$$z_m(t) = \begin{cases} 1, & \text{if } \beta_m(t) \\ 0, & \text{otherwise.} \end{cases}$$

is coded as follows:

```
\begin{equation*}
{z_m(t)} =
\begin{cases}
1,&{\text{if}}\ {\beta }_m(t),\\
{0,}&{\text{otherwise.}}
\end{cases}
\end{equation*}
```

Note that the "&" is used to mark the tabular alignment. This is important to get proper column alignment. Do not use `\quad` or other fixed spaces to try and align the columns. Also, note the use of the `\text` macro for text elements such as "if" and "otherwise."

H. Function Formatting in Equations

Often, there is an easy way to properly format most common functions. Use of the \ in front of the function name will in most cases, provide the correct formatting. When this does not work, the following example provides a solution using the `\text` macro:

$$d_{R}^{KM} = \underset {d_{l}^{KM}} {\text{arg min}} \{ d_{1}^{KM}, \ldots,d_{6}^{KM}\}.$$

is coded as follows:

```
\begin{equation*}
 d_{R}^{KM} = \underset {d_{l}^{KM}}
 {\text{arg min}} \{ d_{1}^{KM},
 \ldots,d_{6}^{KM}\}.
\end{equation*}
```

I. Text Acronyms Inside Equations

This example shows where the acronym "MSE" is coded using `\text{}` to match how it appears in the text.

$$\text{MSE} = \frac {1}{n}\sum _{i=1}^{n}(Y_{i} - \hat {Y_{i}})^{2}$$

```
\begin{equation*}
 \text{MSE} = \frac {1}{n}\sum _{i=1}^{n}
(Y_{i} - \hat {Y_{i}})^{2}
\end{equation*}
```

XV. Conclusion

The conclusion goes here.

Acknowledgments

This should be a simple paragraph before the References to thank those individuals and institutions who have supported your work on this article.

Appendix
Proof of the Zonklar Equations

Use `\appendix` if you have a single appendix: Do not use `\section` anymore after `\appendix`, only `\section*`. If you have multiple appendixes use `\appendices` then use `\section` to start each appendix. You must declare a `\section` before using any `\subsection` or using `\label` (`\appendices` by itself starts a section numbered zero.)

References Section

You can use a bibliography generated by BibTeX as a .bbl file. BibTeX documentation can be easily obtained at: http://mirror.ctan.org/biblio/bibtex/contrib/doc/ The IEEEtran BibTeX style support page is: http://www.michaelshell.org/tex/ieeetran/bibtex/

Simple References

You can manually copy in the resultant .bbl file and set second argument of `\begin` to the number of references (used to reserve space for the reference number labels box).

References

[1] S. Atapattu, R. Fan, P. Dharmawansa, G. Wang, J. Evans, and T. A. Tsiftsis, "Reconfigurable intelligent surface assisted two–way communications: Performance analysis and optimization," *IEEE Transactions on Communications*, vol. 68, no. 10, pp. 6552–6567, 2020.

[2] K. Doppler, M. Rinne, C. Wijting, C. B. Ribeiro, and K. Hugl, "Device-to-device communication as an underlay to lte-advanced networks," *IEEE Commun. Mag.*, vol. 47, no. 12, pp. 42–49, 2009.

[3] (2002) The IEEE website. [Online]. Available: http://www.ieee.org/

Biography Section

If you have an EPS/PDF photo (graphicx package needed), extra braces are needed around the contents of the optional argument to biography to prevent the LaTeX parser from getting confused when it sees the complicated `\includegraphics` command within an optional argument. (You can create your own custom macro containing the `\includegraphics` command to make things simpler here.)

If you include a photo:

Michael Shell Use `\begin{IEEEbiography}` and then for the 1st argument use `\includegraphics` to declare and link the author photo. Use the author name as the 3rd argument followed by the biography text.

If you will not include a photo:

John Doe Use `\begin{IEEEbiographynophoto}` and the author name as the argument followed by the biography text.