Channel Estimation and Spectral Efficiency of Reflecting Intelligent Surface Aided Communications

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WWRF Workshop: THz Waves: Fast Lane Journey to 6G
22 April 2021
Introduction

- Reconfigurable intelligent surfaces (RISs)
  - Low-cost and low-energy consumption passive reflecting elements
  - Customize physical propagation environment
  - Cost-efficient and energy-efficient

- Challenges:
  - Passive reflection in RISs limits the beamforming gains.
  - Performance loss due to limited phase shift resolution.
  - Channel estimation
What is a RIS? Continuous vs. Discrete

Continuous RIS
Mainly used as active transceivers

Received signal

Discrete RIS
Mainly used as passive reflectors

RIS elements
RIS Operation Modes

① Polarization
② Scattering
③ Beamforming
④ Absorption
Channel Estimation with RIS

- RIS is a passive element.
- Channel observed in the final receiver only.
- Product channel observed
- Estimation of the component channels is difficult.

An example system application for downlink transmission.
Channel Estimation Approaches

- Purely passive RIS based CE
- Two-stage approach with matrix factorization and completion [1]
- Matrix-calibration-based cascaded CE [2]
- Active sensors-based CE
- Deep learning [3]
- Compressive sensing [4]

Parametric Channel Model

- Direct channel between BS and RIS

\[ H_{B,R} = \sum_{l=0}^{L_{B,R}} \rho_{B,R,l} \alpha(\phi_{B,R,l}) \alpha^H(\theta_{B,R,l}) \]

- Composite channel

\[ \Omega = \text{diag}(\exp(j\omega_1), \ldots, \exp(j\omega_{N_R})) \in \mathbb{C}^{N_R \times N_R} \]

\[ H = H_{R,M} \Omega H_{B,R} \]

Diagonal, unit-modulus
Proposed Channel Sounding [He-21]

- CE and DT

- CE divided multi-sub-blocks

Stage 1 sounding
\[ Y_0 = W_t^H H(\Omega_0) X_t + W_t^H Z_0, \quad t = 0 \]

Stage 2 sounding
\[ Y_t = W_t^H H(\Omega_t) X_t + W_t^H Z_t, \quad t = 1, \ldots, T \]

Note that we try different phase control matrices

Two-Stage Channel Estimation

- **Stage 1 CE**
  
  To be estimated
  
  \[ H = A(\phi_{R,M})G_0A^H(\theta_{B,R}) \]
  
  \[ G_0 = \text{diag}(\rho_{R,M})A^H(\theta_{R,M})\Omega_0A(\phi_{B,R})\text{diag}(\rho_{B,R}) \]

- **Stage 2 CE**
  
  \[ X_t = \frac{1}{\sqrt{N_B}}A(\hat{\theta}_{B,R}) \]
  
  \[ W_t = \frac{1}{\sqrt{N_M}}A(\hat{\phi}_{R,M}) \]

  \[ A^H(\theta_{B,R})X_t \approx \sqrt{N_B}I, \]
  
  \[ W_t^HA(\phi_{R,M}) \approx \sqrt{N_M}I. \]

  For \( t = 1, \cdots, T \)

  Usually \( L_{B,R} \) and \( L_{R,M} \) are quite small!

\[ Y_0 \]

First stage

\{\hat{\theta}_{B,R}, \hat{\phi}_{R,M}\}

Design of \{X_1, \cdots, X_T\}

and \{W_1, \cdots, W_T\}

\{Y_1, \cdots, Y_T\}

Second stage

\{\hat{\rho}, \hat{\theta}\}
Atomic Norm Minimization (AMN)

- **Stage 1:**
  \[ \phi_{R,M} \min \frac{\mu}{2} \| \tilde{U} \|_{A_M} + \frac{1}{2} \| Y_0 - W_0^H \tilde{U} \|_F^2, \]
  \[ \theta_{B,R} \min \frac{\eta}{2} \| \tilde{U} \|_{A_M} + \frac{1}{2} \| Y_0^H - X_0^H \tilde{U} \|_F^2, \]
  \[ \tilde{U} = A(\phi_{R,M}) G_0 A^H(\theta_{B,R}) X_0 = A(\phi_{R,M}) \tilde{C} \]
  \[ \tilde{U} = A(\theta_{B,R}) G_0^H A^H(\phi_{R,M}) W_0 = A(\theta_{B,R}) \tilde{C} \]
  \[ \tilde{C} = G_0 A^H(\theta_{B,R}) X_0 \]

- **Stage 2:**
  \[ \tilde{\theta}_i \]
  \[ \{ \tilde{v}, \tilde{h}_i, \tilde{z} \} = \arg \min_{v,h_i,z} 0.5\nu_i z + \frac{\nu_i}{2N_R} \text{Tr}(\text{Toep}(v)) \]
  \[ + \frac{1}{2} \| [Y]_{i,:} - \sqrt{N_B N_M} \Omega h_i \|_2^2 \]
  \[ \text{s.t.} \begin{bmatrix} \text{Toep}(v) & h_i^H \\ h_i & z \end{bmatrix} \succeq 0, \text{ for } i = 1, \cdots, L_{B,R} L_{R,M}; \]
  \[ \hat{\nu}_i = (\alpha(\tilde{\theta}_i))^\dagger \hat{h}_i, \]
Estimation Performance

\[
\text{MSE}(\sin(\theta_{B,R})) = \mathbb{E}\left[ \frac{\|\sin(\theta_{B,R}) - \sin(\hat{\theta}_{B,R})\|^2}{L_{B,R}} \right], \\
\text{MSE}(\sin(\phi_{R,M})) = \mathbb{E}\left[ \frac{\|\sin(\phi_{R,M}) - \sin(\hat{\phi}_{R,M})\|^2}{L_{R,M}} \right], \\
\text{MSE}(\sin(\Delta)) = \mathbb{E}\left[ \frac{\|\sin(\Delta) - \sin(\hat{\Delta})\|^2}{L_{B,R}L_{R,M}} \right], \\
[\Delta]_{mn} = \text{asin}\left(\sin([\phi_{B,R}]_n) - \sin([\theta_{R,M}]_m)\right) \\
\]

\[N_B = N_M = 16, \quad N_R = 32\]
\[L_{B,R} = L_{R,M} = 2\]

Training overhead 1
\[N_0 = M_0 = T = 10 \text{ with } T_t = 40\]

Training overhead 2
\[N_0 = M_0 = T = 14 \text{ with } T_t = 56\]
Spectral Efficiency Performance

\[
R = \mathbb{E} \left[ \frac{T_c - T_t}{T_c} \log_2 \left( 1 + \frac{|w^H \hat{H} f|^2}{\sigma^2 + \text{var}(w^H H_c(\Omega^*) f)} \right) \right]
\]

\[N_B = N_M = 16, \quad N_R = 32\]

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Training overhead 1
\[N_0 = M_0 = T = 10 \text{ with } T_t = 40\]

Training overhead 2
\[N_0 = M_0 = T = 14 \text{ with } T_t = 56\]
Summary and Conclusions

- RIS channel estimation is challenging and not always feasible
- We assumed known sparse channel structure to derive a superresolution algorithm based on ANM.
- Two-stage optimization problems.
- RIS phase control matrix designed to maximize the power of effective channel based on the estimates in the second stage.
- Joint beamforming at BS and MS
- Active receiver at RIS could enhance and simplify CE.
Hybrid Relay – RIS [Nguyen-21]

- Very large RISs are required [1], [2].
- A few more elements only provide small gain.

Replacing a few passive elements by relays:
⇒ Small loss in passive BF gains
⇒ Significant active relaying gains

Hybrid relay-reflecting intelligent surface (HR-RIS)

HR-RIS Architectures

- Configure and fix in advance during manufacturing ⇒ fixed HR-RIS architecture [3]
- Dynamically optimize based on CSI ⇒ dynamic HR-RIS architecture [3]
- Active element: RF, power amp., phase shifter
- Passive element: only phase shifter

System Model

- The received signal at the MS:

\[ y = H_r \Phi H_t x + H_r \Psi H_t x + H_r \Psi n_H + n_{MS} \]  \hspace{1cm} (1)

- reflected signal  \hspace{1cm} relayed signal  \hspace{1cm} amplified noise  \hspace{1cm} noise at MS

- \( H_r \Psi n_H \sim CN( 0, \sigma^2 H_r \Psi \Psi^H H_r^H ) \)

- \( n_{MS} \sim CN( 0, \sigma^2 I_{N_r} ) \)

- \( n = H_r \Psi n_H + n_{MS} \sim CN( 0, \sigma^2 ( I_{N_r} + H_r \Psi \Psi^H H_r^H ) ) \)

\[ \Rightarrow y = H_r \Psi H_t x + n \]  \hspace{1cm} (2)

- \( \alpha_n = |\alpha_n| e^{j\theta_n} \)

\( \Psi \) contains only active coefficients

\( \Phi \) contains only passive coefficients

A: positions of \( K \) active elements
SE Maximization

- Spectral efficiency (SE)

\[
f_0([\alpha_n]) = \log_2 |I_{N_r} + \rho H_r Y H_t H_t^H Y^H H_r^H R^{-1}| \leq \log_2 |R + \rho H_r Y H_t H_t^H Y^H H_r^H| = \mathcal{f}([\alpha_n])
\]

\[R = I_{N_r} + H_r \Psi \Psi^H H_r^H, \quad \rho = P_{BS}/\sigma^2\]

- Transmit power of active elements:

\[P_a = \text{trace}(\Psi (P_{BS} H_t H_t^H + \sigma^2 I_{N_r}) \Psi^H)\]

- HR-RIS is designed to maximize the SE

\[(P0) \quad \begin{cases} \text{maximize} & \mathcal{f}([\alpha_n]) \\ \text{subject to} & |\alpha_n| = 1, \forall n \notin A \\
& P_a \leq P_a^{max} \end{cases}\]
Alternating Optimization Approach

- Let $r_n$ be the $n$th column of $H_r$, $t_n^H$ be the $n$th row of $H_t$.
- $\Upsilon$ and $\Psi$ are diagonal $\Rightarrow H_r \Upsilon H_t = \sum_{n=1}^{N} \alpha_n r_n t_n^H$, $H_r \Psi = \sum_{n=1}^{N} \alpha_n r_n$.

\[ \Rightarrow f(\alpha_n) = \log_2 |A_n + |\alpha_n|^2 B_n + \alpha_n C_n + \alpha_n^* C_n^H| \]  

\[ P_a = \sum_{n \in A} |\alpha_n|^2 \xi_n, \text{ where } \xi_n = \sigma^2 + P_{BS} ||t_n||^2 \]  

\[ (P) \text{ maximize } f(\alpha_n) \]

subject to

\[ |\alpha_n| = 1, n \notin A \]

\[ |\alpha_n|^2 \leq \frac{P_a^{max} - \sum_{i \in A, i \neq n} |\alpha_i|^2 \xi_i}{\xi_n}, n \in A \]
Alternating Optimization (2)

\[ f(\alpha_n) = \log_2|A_n + |\alpha_n|^2B_n + \alpha_nC_n + \alpha_n^*C_n^H| \]

\[ = \log_2|A_n| + \log_2|I_{N_r} + |\alpha_n|^2A_n^{-1}B_n + \alpha_nA_n^{-1}C_n + \alpha_n^*A_n^{-1}C_n^H| \]

\[ = \log_2|A_n| + \log_2|D_n| + \log_2|I_{N_r} + \alpha_nE_n^{-1}C_n + \alpha_n^*E_n^{-1}C_n^H| \qquad (E_n \triangleq A_nD_n) \]

\[ = \log_2|A_n| + \log_2(1 + |\alpha_n|^2\gamma_n) + \log_2(1 + |\alpha_n|^2|\lambda_n|^2 + 2\Re(\alpha_n\lambda_n) + c_n) \quad [4] \]

\[ \text{sole non-zero eigenvalue of } A_n^{-1}B_n \quad \text{sole non-zero eigenvalue of } E_n^{-1}C_n \]

- Phase of \( \alpha_n^* \) is \(- \arg(\lambda_n)\)
- \( f(\alpha_n^*) \) monotonically increases with \( |\alpha_n^*| \)

\[ \alpha_n^* = \begin{cases} 
\sqrt{\frac{p_{\text{max}} - p_a}{\xi_n}} e^{-j\arg(\lambda_n)}, & n \in \mathbb{A} \\
e^{-j\arg(\lambda_n)}, & \text{otherwise} \end{cases} \quad [9] \]

Alternating Optimization Algorithm

\[ |\alpha_n^*|^2 = \frac{p_{a}^{max} - \sum_{i \in \mathbb{A}, i \neq n} |\alpha_i|^2 \xi_i}{\sigma^2 + P_{BS} ||t_n||^2}, n \in \mathbb{A} \quad (10) \]

→ With a limited power budget \( p_{a}^{max} \), the HR-RIS with a small number of active elements is easider to attain SE gains.
→ With a fixed \( p_{a}^{max} \), a lower \( P_{BS} \) and/or smaller \( ||t_n||^2 \) (caused by severe path loss) can result in a higher \( |\alpha_n^*|^2 \), and thus, provide a higher SE gains.

**Algorithm 1** Find \( \Upsilon^* \) for HR-RIS

**Input:** \( H_t, H_r, \mathbb{A} \).

**Output:** \( \Upsilon^* \).

1. Randomly generate \( \{\alpha_n\} \) with \( |\alpha_n| = 1 \) for \( n \notin \mathbb{A} \) and \( \sum_{n \in \mathbb{A}} |\alpha_n|^2 \xi_n = p_{a}^{max} \) for \( n \in \mathbb{A} \).
2. **while** not converge **do**
3. **for** \( n = 1 \rightarrow N \) **do**
4. Compute \( A_n, B_n, \) and \( C_n \) based on (9)-(14).
5. \( D_n = I_{N_r} + |\alpha_n|^2 A_n^{-1} B_n, E_n = A_n D_n \).
6. Find \( \lambda_n \) as the sole non-zero eigenvalue of \( E_n^{-1} C_n \).
7. Compute \( \alpha_n^* \) based on (23).
8. **end for**
9. Check convergence.
10. **end while**
11. \( \Upsilon^* = \text{diag} \{\alpha_1^*, \ldots, \alpha_N^*\} \).
Example: SE vs. TX Power

The proposed HR-RIS scheme can provide significant improvement in SE compared with the conventional RIS.

- The SE improvement is more significant at low $P_{BS}$.

$N_t = 32, \; N_r = 2, \; N = 50, \; K = 4$
Example: SE vs. No. Active Elements

- Deploying more active elements at the HR-RIS does not always provide a higher SE.
- For low $P_a^{max}$, HR-RIS with a large number of active elements can have performance loss.

$N_t = 32, N_r = 2, N = 50, P_{BS} = 30$ dBm
Example: SE vs. Distance

- Both RIS and HR-RIS performs the best when they are close to the MS.
- When the RIS/HR-RIS moves far away from the BS, HR-RIS attains more significant active beamforming gains (due to more severe path loss).

\[ N_t = 32, N_r = 2, N = 50, P_{BS} = 30 \text{ dBm}, \text{ and } P_{a}^{\text{max}} = 0 \text{ dBm} \]
Summary and Conclusions

- HR-RIS can provide semi-passive beamforming gains to achieve higher SE compared to the conventional RIS.
- Only a few elements are connected to PA to serve as active relays, while the other sever as passive reflection elements.
- HR-RIS can be designed and optimized by alternating optimization:
  - A small number of active elements is sufficient for a satisfying SE gain. Deploying many active elements does not always provide higher SE.
  - HR-RIS can attain a more significant SE gain when the transmit power at the BS is small and/or when the BS-HR-RIS distance is large.
Future Research

- Hybrid receive architectures can enhance the CE and positioning
- Position aware beamforming can enhance CE and communications
- SE and energy efficiency optimization of HR-RIS
- Implementation aspects