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LEO Satellite Networks
Ground Contact/Energy Transmission Period

International collaboration for SSP → Worldwide Ground station implementation

- Total satellite ground contact
- Total ground contact period with sunlight
- Average path loss of wireless power transmission
- Difference in impact comparing SSO LEO, MEO, GEO;

SSO = Sun-synchronous Orbit (low-earth orbit zone)
MEO = medium earth orbit
GEO = geosynchronous orbit

Distributed ground station coverage area
LEO Implementation

Pros
• Lower altitudes → lower power loss
• Lower transmission power per unit → Less Environmental Impact
• Higher Number of Satellites → Higher reliability
• Lower Cost of Development and Launching

Cons
• LEO has 10 to 15mins contact period per ground stations
  → Multiple Ground Stations Needed → Handoff Process Needed
• LEO may use multiple satellite transmission → Synchronization Needed
• International Cooperation and Unified Policy;
• Routing or Battery Storage if a cluster is not in ground station field of view;

Applications:
SSP to remote and local area
Articles on SSP via LEO Satellite Networks


Multi-Satellite Synchronization?

- Different Doppler
- Different distance to ground
Time Synchronization

\[ S_T(t) = \sum_m s_m(t - \tau_m) \]

- Time offsets: \[ \{\tau_m\}_{m=1}^{K} \]
Frequency Synchronization

\[ r_T(t) = \sum_m e^{j2\pi (f_c + \Delta f_m) t} \]

- Frequency offsets: \( \{\Delta f_m\}_{m=1}^K \)
Idea!

- Design a proper training waveform for time synchronization which
  - Handles multi-satellite scenario
  - Could be easily detectable

- Use the detected waveform to estimate frequency offset which
  - Handles the unknown channel Impulse response
  - Computationally efficient


Outline

- System Model
- Proposed Technique
  - Time Synchronization and Weighted OFDMA waveform
  - Frequency Synchronization
- Simulation Results
- Future Works and Conclusion
Outline

- **System Model**
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System Model

- Received signal by target (power station at earth or the leader satellite):

\[ r_T(t) = \sum_m e^{j2\pi f_m t} h_m s_m(t - \tau_m) + \nu(t) \]

- \( s_m(t) \) : Training waveform of the \( m \)-th satellite
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Time Synchronization

- Allocating a set of OFDMA subcarriers to the $m$-th satellite:

\[ S_m(kT_s) = \sum_{p \in \kappa_m} e^{j2\pi p \Delta f k T_s}, 1 \leq k \leq N \]

- Where: $\Delta f = \frac{1}{NT_s}$ is the OFDM subcarrier spacing

- $N_s = |\kappa_m|$ Number of allocated sub-carrier
Time Synchronization

\[ \hat{t}_m = \arg\max_k \left\{ \prod_{p \in \kappa_m} s_m^H r_{k+p} \right\} \]

Select \( r_{k:M:k+MN-1} \)

\[
\begin{align*}
(s^{(1,1)}(N-n))^* & \rightarrow \argmax \rightarrow k_1^* \\
(s^{(1,N_s})(N-n))^* & \rightarrow \argmax \rightarrow k_2^* \\
(s^{(2,1)}(N-n))^* & \rightarrow \argmax \rightarrow k_3^* \\
(s^{(2,N_s})(N-n))^* & \rightarrow \argmax \rightarrow k_4^* \\
\vdots & \vdots \vdots \vdots \\
(s^{(M,1)}(N-n))^* & \rightarrow \argmax \rightarrow k_M^* \\
(s^{(M,N_s)}(N-n))^* & \rightarrow \argmax \rightarrow k_{M+1}^* \\
\end{align*}
\]
Time Synchronization
Weighted OFDMA waveform

- Increasing $N_s$ results in high Peak to Average Power Ratio (PAPR)

\[
G_{PAPR} = \frac{\max |s_k^{(m)}|^2}{\frac{1}{N} \sum_k |s_k^{(m)}|^2}
\]

- $N_s = 1, G_{PAPR} = 0 \text{ dB}$
- $N_s = 2, G_{PAPR} = 3 \text{ dB}$
- $N_s = 4, G_{PAPR} = 6 \text{ dB}$
- $N_s = 8, G_{PAPR} = 9 \text{ dB}$
- $N_s = 16, G_{PAPR} = 11 \text{ dB}$
Weighted OFDMA waveform

- Weighted OFDMA waveform

\[ S_m(kT_s) = \sum_{p \in \kappa_m} w_p^{(m)} e^{j2\pi p\Delta f k T_s}, 1 \leq k \leq N \]

\[ \hat{w}^{(m)} = \arg \max_{w^{(m)}} \left\{ c_N^{(m)} - 2c_{1:N-1}^{(m)} - \gamma G_{PAPR} \right\} \]

\[ c_k^{(m)} = \prod_{p \in \kappa_m} \left| \left( w_p^{(m)} S_m \right)^H r_{k:k+N-1} \right| \]

\[ G_{PAPR} = \frac{\max |s_k^{(m)}|^2}{\frac{1}{N} \sum_k |s_k^{(m)}|^2} \]
Weighted OFDMA waveform

\[ \hat{m} = \arg \max \left\{ \prod_{p \in \kappa_m} \left( \frac{w_p^{(m)} s_m}{w_p^{(m+N)_{k+1}}} \right)^H r_{k:k+N-1} \right\} \]
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Frequency Synchronization

- Time Synchronization
  - Select the training waveform
    - RLS based channel estimation
    - RLS based frequency offset estimation
  - $\hat{h}_k$
  - $\hat{e}_k$
Frequency Synchronization

- RLS based channel estimation minimizes:

\[ C(\hat{h}_k) = \sum_{n=0}^{k} \lambda_1^{(n-k)} |e_{h|\epsilon}(n)|^2 \]

Where:

\[ e_{h|\epsilon}(n) = e^{-j \frac{2\pi \hat{e}_{k-1}}{N} r_k - \hat{h}_{k-1} s_k} \]

Linear function respect to \( \hat{h} \)

- RLS based frequency offset estimation minimizes:

\[ C(\hat{e}_k) = \sum_{n=0}^{k} \lambda_2^{(n-k)} |e_{\epsilon|h}(n)|^2 \]

Where:

\[ e_{\epsilon|h}(n) = r_k - e^{j \frac{2\pi \hat{e}_{k-1}}{N} r_k - \hat{h}_k s_k} \]

Non-Linear function respect to \( \hat{e} \)
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Simulation Results

- Time Synchronization performance:

\[
MSE_\tau = \frac{\sum_{m=1}^{K} |\tau_m - \hat{\tau}_m|^2}{K}
\]

- Frequency synchronization and Channel estimator performance:

\[
MSE_\varepsilon = \frac{\sum_{m=1}^{K} |\varepsilon_m - \hat{\varepsilon}_m|^2}{K}
\]

\[
MSE_h = \frac{\sum_{m=1}^{K} |h_m - \hat{h}_m|^2}{K}
\]
Simulation Results
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Future Works

- Proposing a frame-based structure for the proposed waveform in order to enable time-frequency offset tracking
- Extend the proposed method to handle frequency dispersive channels such as ionosphere layers
Conclusion

- Time-frequency Synchronization is vital for SSP
- Weighted OFDM sub-carriers for ToA estimation which handles
  - Multi-satellite scenario
  - Low PAPR
- Joint CIR and CFO estimation
- Low computational Complexity
Thank You!

Any Question?