Adaptive Array Technology for Navigation in Challenging Signal Environments

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Introduction & Outline

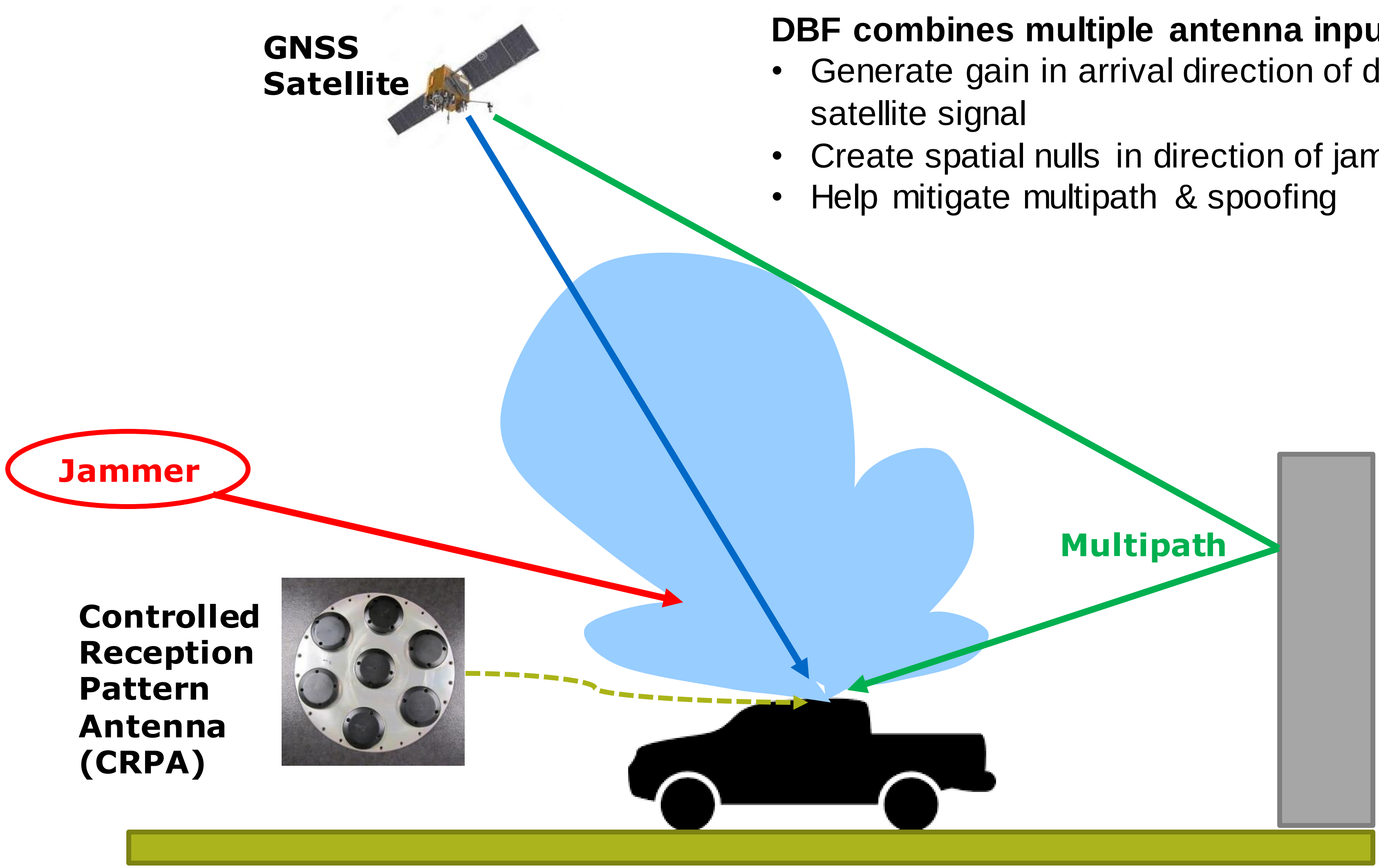
- Adaptive antenna array technologies are becoming increasingly important for Positioning, Navigation and Timing (PNT) in challenging signal environments
- Current application: GNSS
  - Digital Beam Forming (DBF) processing overview
  - DBF compared to simple adaptive nulling
  - DBF limitations
  - Future R&D trends in GNSS adaptive array technology
- Emerging application: 5G "Picocells"
  - 5G cellular architectures will use adaptive array technology to achieve high data rates, spectrum reuse and communications robustness
  - PNT implications:
    - 5G system architectures will require improved (relative) PNT to operate effectively
    - 5G Picocells will be a source of PNT information in constrained environments

There will be an adaptive array in your PNT future

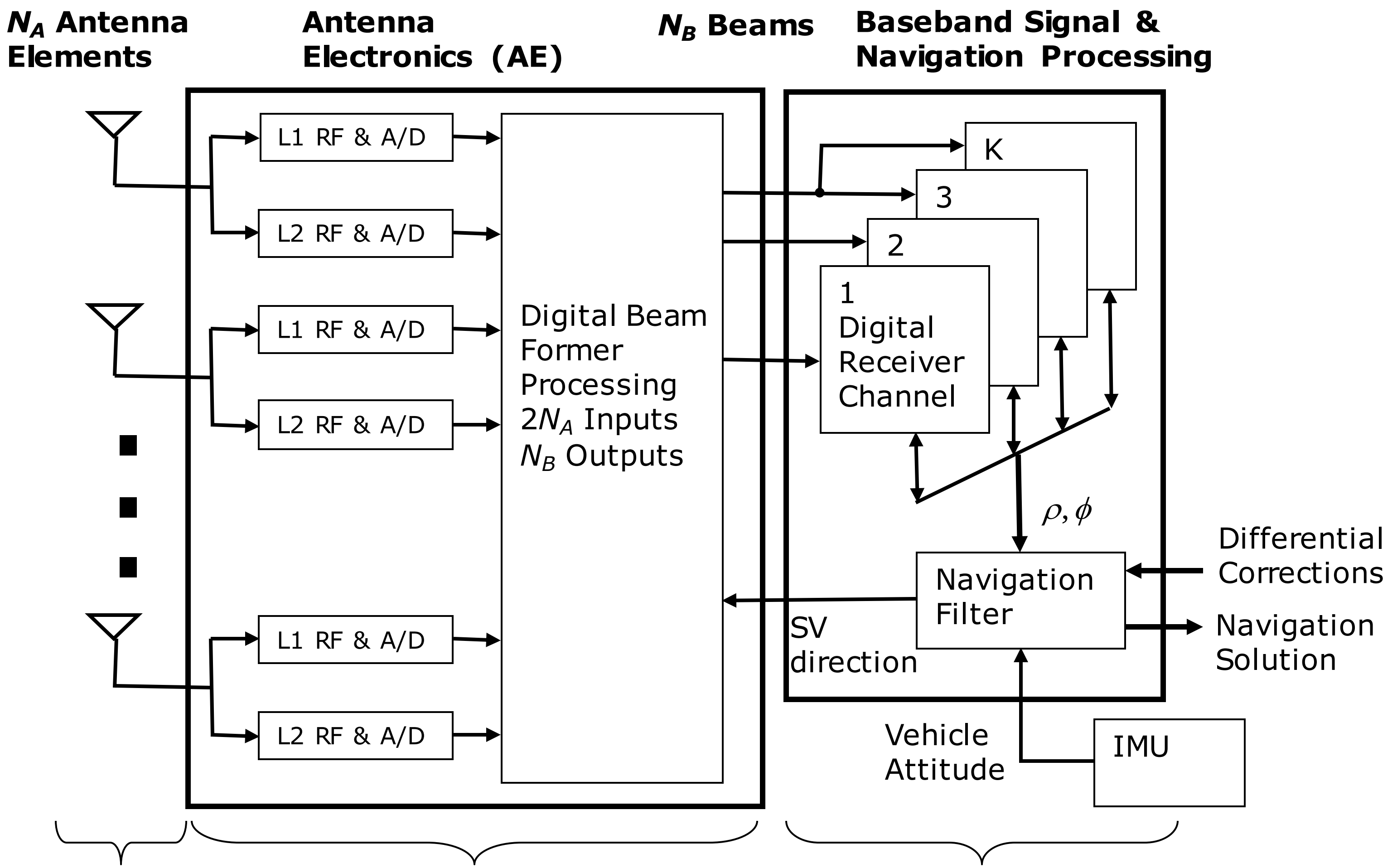
Digital Beam Forming for GNSS

DBF combines multiple antenna inputs to:

- Generate gain in arrival direction of desired satellite signal
- Create spatial nulls in direction of jamming
- Help mitigate multipath & spoofing



DBF/GPS Block Diagram – Precorrelation Processing



Typical System Configuration:

- 4-7 Element CRPA
- 14 RF x 24 Beams
- 24 Channels

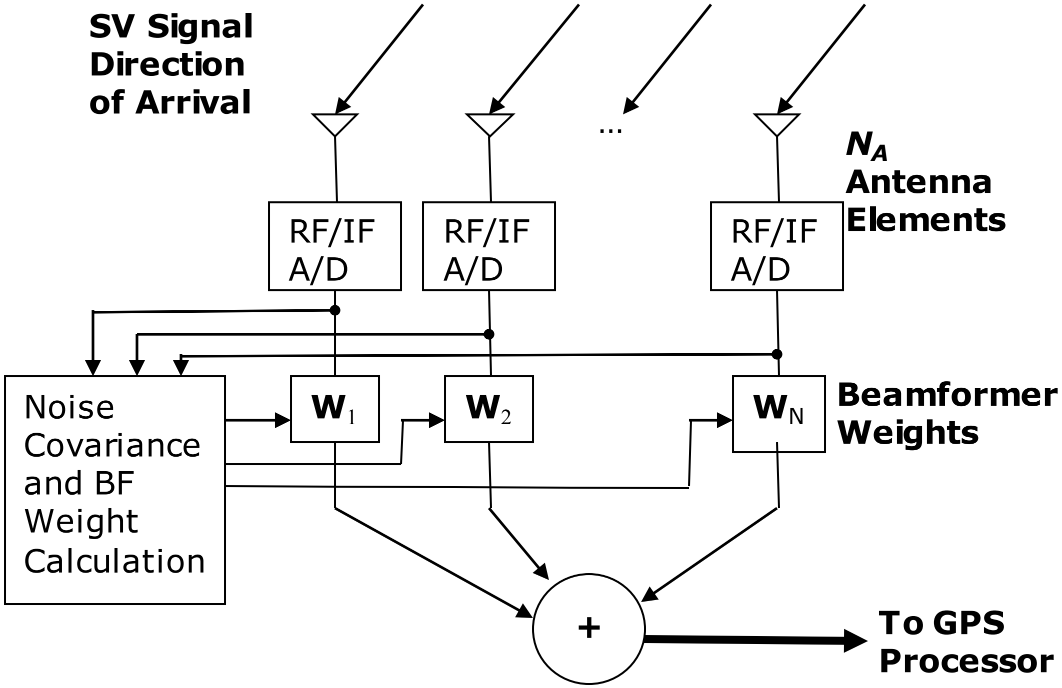
DBF Processing Block Diagram for Single Beam

Weight Vector (Complex):

$$\boldsymbol{w} = [w_1, w_2, \ldots, wn]^T$$

Weights Chosen to:

- Constrain output pattern in arrival direction of desired SV signal
- Minimize output power (noise+jamming)



Single SV Constraint:

$$\left.\begin{array}{l}\text{Minimize: } \boldsymbol{w}^{*}\boldsymbol{R}_{v}\boldsymbol{w}, \\ \text{Subject to: } \hat{\boldsymbol{a}}^{*}\boldsymbol{w} = 1\end{array}\right\} \Rightarrow \boldsymbol{w} = \frac{\boldsymbol{R}_v^{-1}\hat{\boldsymbol{a}}}{\hat{\boldsymbol{a}}^{*}\boldsymbol{R}_v^{-1}\hat{\boldsymbol{a}}}$$

$\boldsymbol{R}_v$ = Noise Covariance

$\hat{\boldsymbol{a}}$ = Estimated CRPA manifold

- CRPA manifold is the gain & phase of each antenna element as a function of AZ/EL in antenna coordinates
- Requires platform orientation– which may be a problem for some applications

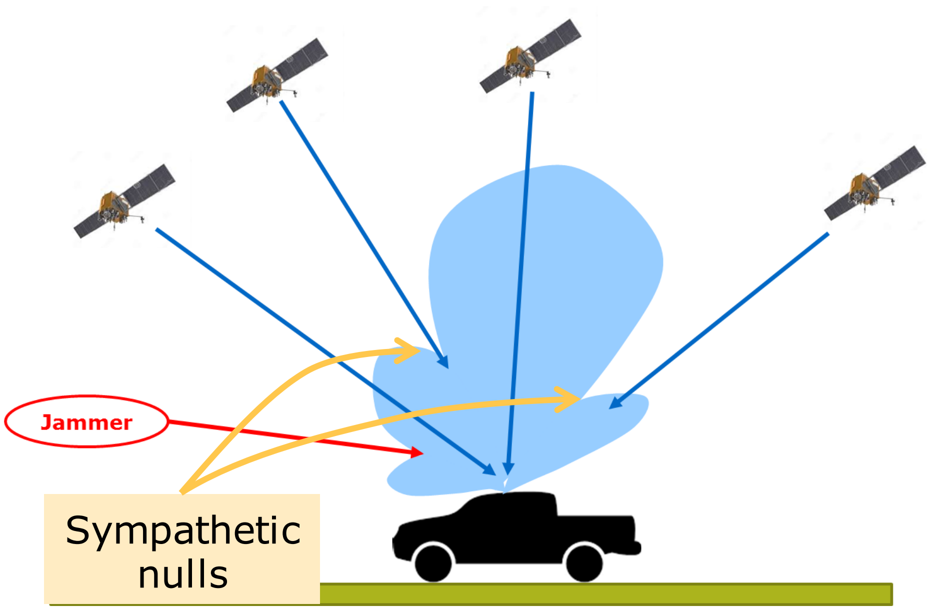
DBF vs. Nulling-Only Algorithms

- Spatial nulling does not require antenna manifold information or platform attitude, as they minimize power without the SV gain constraint
- Resulting SNR is usually poorer than DBF, resulting in less measurement availability
- Sympathetic nulls can result in unintentional degradation in SV availability
- May suffer from measurement distortion– potentially large PR and CP errors induced by nulling action

Nulling Constraint:

$$\left.\begin{array}{ll}\text{Minimize:} & \boldsymbol{w}^{*}\boldsymbol{R}_{v}\boldsymbol{w} \\ \text{Subject to:} & \boldsymbol{u}^{T}\boldsymbol{w} = 1\end{array}\right\} \Rightarrow \boldsymbol{w} = \frac{\boldsymbol{R}_{v}^{-1}\boldsymbol{u}}{\boldsymbol{u}\boldsymbol{R}_{v}^{-1}\boldsymbol{u}}$$

$\boldsymbol{u} = [1, 0, \ldots, 0]^{T}$ (Reference element constraint)



DBF Limitations

- SV gain constraint helps to minimize CP measurement distortions (subject to accuracy of CRPA manifold data)
- PR measurement distortions can be present due to CRPA group delay variation over AZ/EL
  - Same is true for all antennas, but compensation is more complex due to adaptive nature of the processing
- Null depth for spatial-only DBF is best at center frequency and degrades with frequency
  - Spatial-only DBF is less effective for wider-band signals (e.g. BOC)
  - Space-Time or Space-Frequency Adaptive Processing (STAP/SFAP) are effective for use with wider band signals and jamming

GNSS Adaptive Array Technology Directions

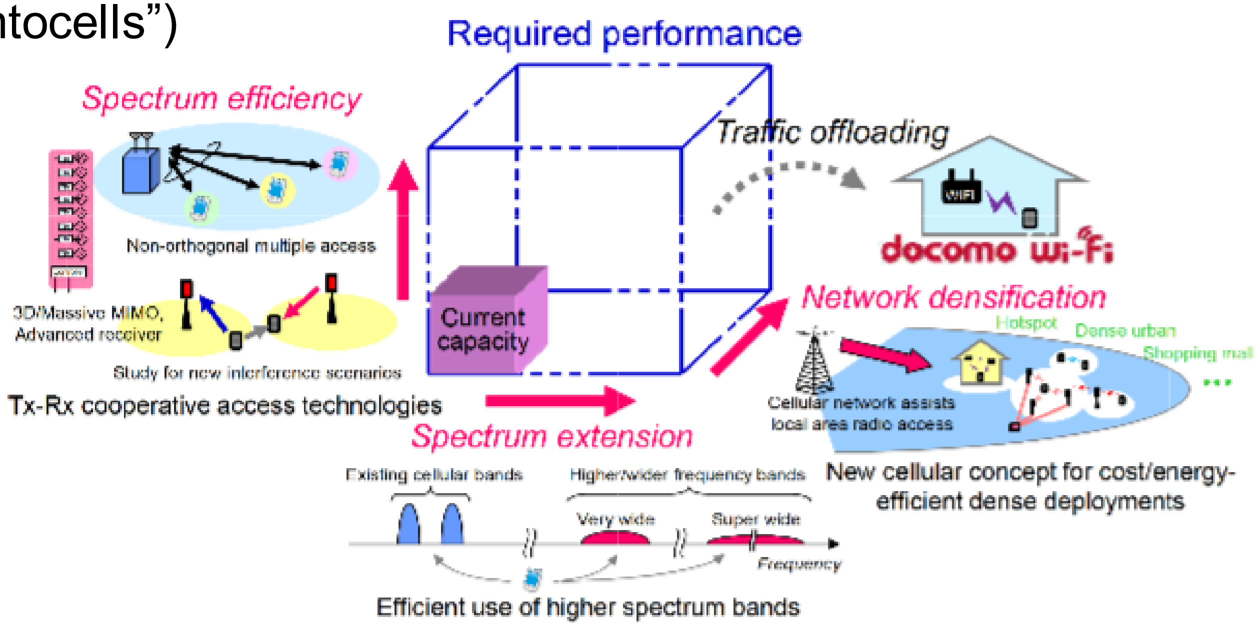
- "Distortion-less" algorithms that reduce nulling-induced PR and CP measurement errors
  - SFAP/STAP algorithms can be constructed to theoretically induce zero errors-- dependent on quality of the array manifold data
  - Computational complexity can increase significantly
- Post-correlation techniques
  - Basic approach using Prompt correlator tap is theoretically similar to pre-correlation– but with a redistribution of computation that may be more complex
  - Can do beam-steering without full manifold data (e.g., "blind beamforming"), but measurement distortions are still an issue
  - Permitting adaptation for correlator taps enables spatial discrimination of multipath and spoofers
- Techniques for in-situ determination of array manifold
  - Array manifold knowledge is a limitation for high-accuracy applications

5G Cellular PNT

- 5G technology trends
- 5G architectures
- Directional communications with massive MIMO (Multiple Input Multiple Output)
- Potential PNT implications of 5G

Elements of 5G Developments

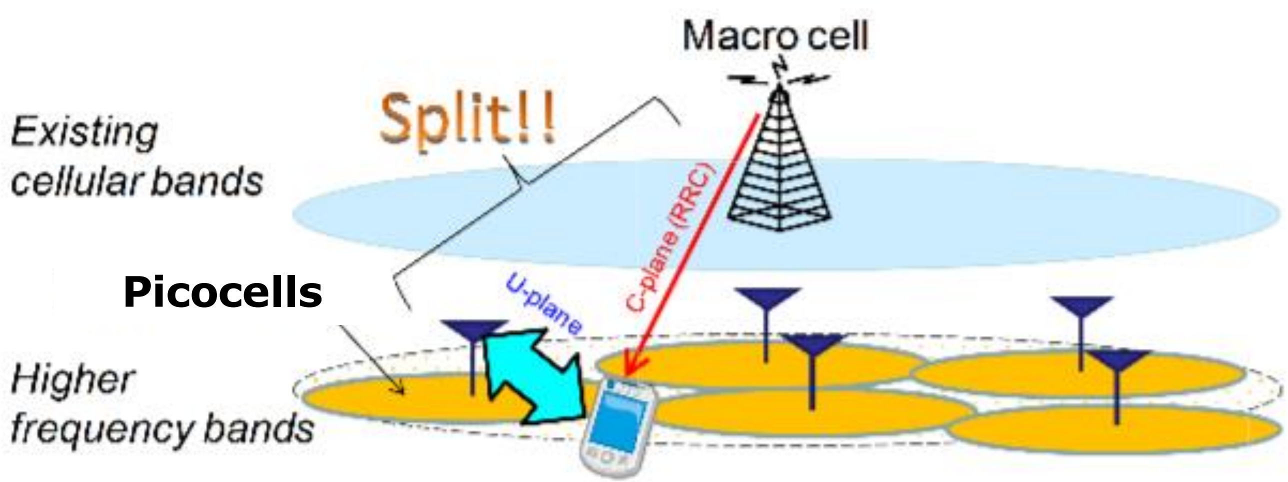
- Move to higher frequencies (>10 GHz, including mm-wave and maybe THz and light) for higher data bandwidth
- Move to directional links to support spectral reuse, high data rates and indoor and urban operation
- Both of the these point toward dense networks of smaller cells (“picocells” or “”femtocells”)



From: DOCOMO 5G White Paper, “5G Radio Access: Requirements, Concept and Technologies”, NTT DOCOMO Inc., July 2014, https://www.nttdocomo.co.jp/english/binary/pdf/corporate/technology/whitepaper_5g/…
DOCOMO_5G_White_Paper.pdf

Future High-Level 5G Architecture

- Control Plane (based on 4G/LTE) will be separate from User Plane
- Control Plane provides lower data rate services and enables backbone network management function to have “global” view of who is in the network
- User Plane provides shorter range, high bandwidth connectivity using directional antennas arrays with tens (or even hundreds) of elements



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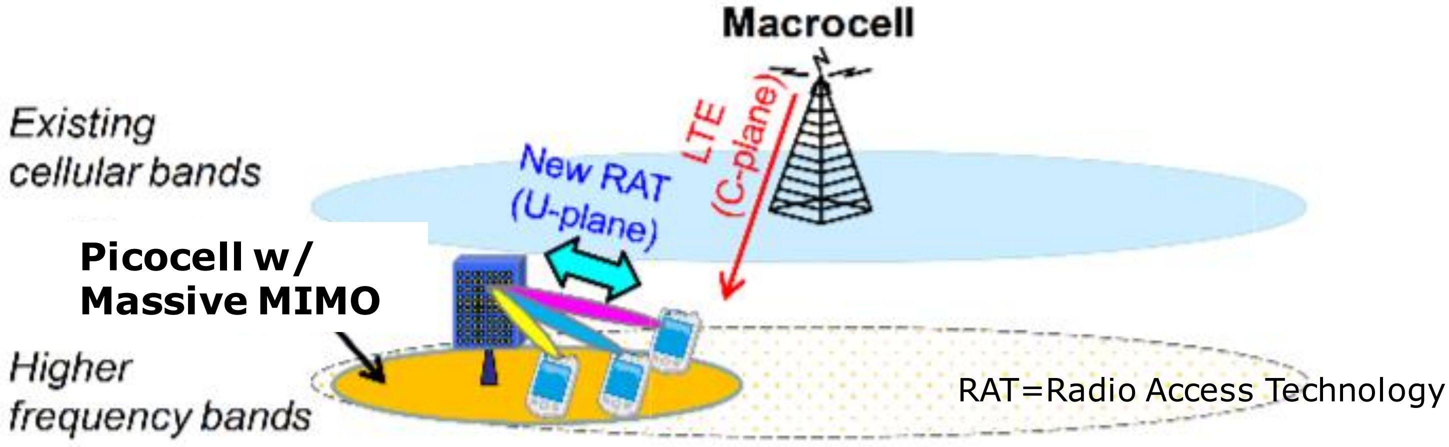
Directional Comms with Massive MIMO

- MIMO (Multiple Input Multiple Output) enables high bandwidth comms in fading (multipath) channels by using multiple antenna inputs to adapt to channel – can do this without knowledge of user location, but this adds to processing complexity
- Directional capability will enable multiple users to be serviced in a picocell (at different frequencies)
- Spectrum reuse by nearby picocells enabled by directional links (narrow beamwidth and limited range of mm-wave frequencies)



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PNT Implications of 5G Architectures

- Efficient operation of directional links will require some level of knowledge of user location wrt picocells
  - Information from the Control Plane may not be available and/or sufficient – particular for faster moving vehicles or indoors
  - Handover of a user from one picocell to another may need to happen faster than the omnidirectional Control Plane can respond
- Picocells will have ability to do direction of arrival and ranging in order to maintain connectivity with user nodes
  - This can be exploited by the user node for positioning and location based services– particularly for indoor and dense urban environments
  - Network management will need decentralized tracking of user locations to maintain different resolution of position information
- Proliferation of adaptive array technology will drive down costs for other applications
  - Millimeter-wave transmit/receive (T/R) modules will become commodity items, analogous to what cell phones have done for GPS chips

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Summary

- Adaptive array technologies have many advantages for PNT
  - Multipath mitigation
  - Jamming and spoofing mitigation
- 5G picocells will be synergistic with PNT in challenged environments
  - Indoor, urban
  - Will necessitate development of distributed networked PNT processing and infrastructure
- Availability of adaptive array technology will increase with deployment of 5G – costs can be expected to drop dramatically
- In addition to GNSS, adaptive array technologies can be employed to support short range, relative PNT applications
  - E.g., vehicle-to-vehicle communications and relative positioning