Security Issues in Spectrum Sharing Between Radar and Communication Systems

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Outline

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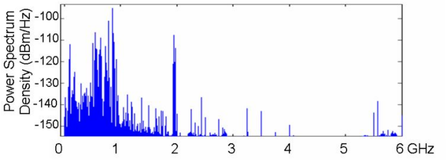
The Need for Spectrum Sharing

- Radar and communications jointly consume most of the spectrum below 6 GHz.
- Until recently, allocated spectrum for commercial and non-commercial purposes (i.e. military radar) were on distinct bands.
- S-band radar ($2-4$ GHz) partially overlaps with LTE and WiMax systems.

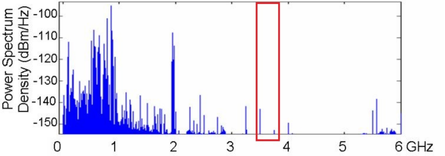


Freq (GHz)	0~1	1~2	2~3	3~4	4~5	5~6
Utilization(%)	54.4	35.1	7.6	0.25	0.128	4.6

Figure: Spectrum utilization in downtown Berkeley (UC Berkeley, 2007).

The Need for Spectrum Sharing

- As the number of connected devices grows, these band distinctions limit a more efficient use of the spectrum.
- Spectrum regulators have proposed to make the $3.55 - 3.7$ GHz band (used for military radar) available to commercial cellular systems.
- The need arises for an efficient use of the spectrum for both systems, without one interfering with the other $\rightarrow$ Spectrum sharing approaches.



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Existing Approaches for Spectrum Sharing

1. Avoid interference by large spatial separation.

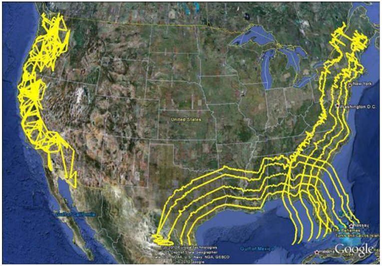

Figure: Shipborne radar exclusion zones in 3.5 GHz band (NTIA 2015).

2. Dynamic spectrum access based on spectrum sensing.

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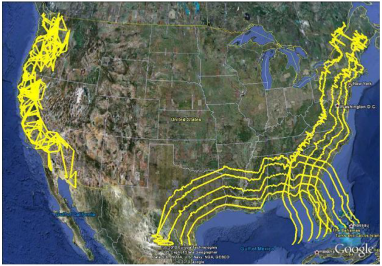


Figure: Shipborne radar exclusion zones in 3.5 GHz band (NTIA 2015).

2. Dynamic spectrum access based on spectrum sensing.
3. **Spatial multiplexing enabled by the multiple antennas at both the radar and communication systems.**

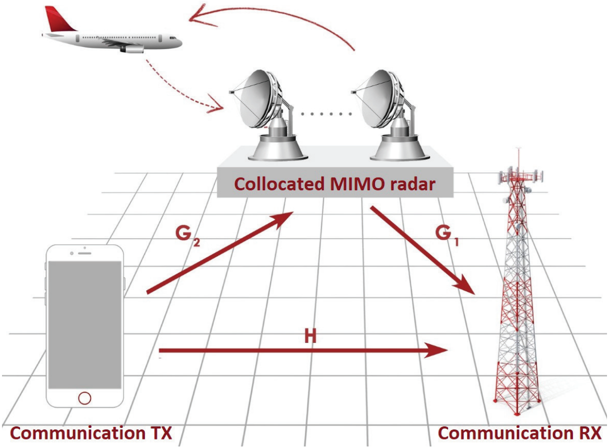
MIMO Shared Spectrum Literature

- Methods that address the objectives of one or the other system but not both.
  - Nullspace projection implemented by radar to reduce interference towards the communication system [Sodagari et al. 2012] or vice versa.
  - Nullspace projection precoding to avoid interference is possible on either the radar or the communication systems but not on both [Mahal et al.,2017].
- Co-design methods that address the constraints of both systems.
  - Communication system and/or radar precoding schemes are co-designed in order to maximize an objective function of one user (typically the radar), subject to meeting certain constraints for the other (typically the communication system) [Li, Kumar, and Petropulu, 2016] [Li, Petropulu, Trappe, 2016] [Li and Petropulu, 2017]

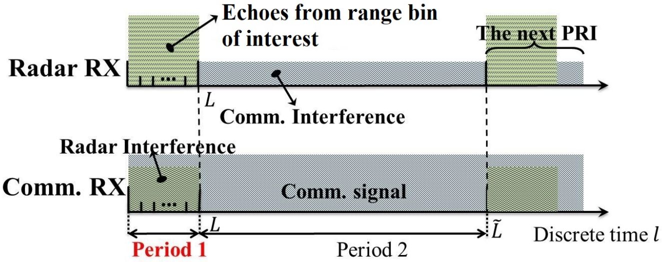
Outline

Spectrum Sharing Formulation

- $M_R^r \times M_R^t$ MIMO radar
- $M_C^r \times M_C^t$ MIMO communication system



- Interference at the radar occurs when the radar is listening, or forwarding the obtained samples to the radar fusion center.



Interference During Spectrum Sharing

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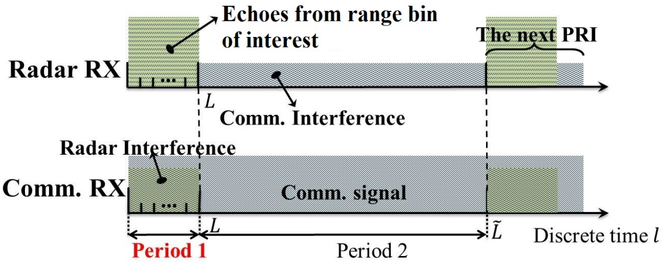

- Use transmit precoding to limit the interference to the radar.

The Coexistence Signal Model

- The received signals at the radar and communication RX are

Radar fusion center: (1a)

$$\boldsymbol{\Omega} \circ \mathbf{Y}_R = \boldsymbol{\Omega} \circ \big(\underbrace{\mathbf{DPS}}_{\text{signal}} + \underbrace{\mathbf{CPS} + \mathbf{G}_2\mathbf{X}\boldsymbol{\Lambda}_2}_{\text{interference}} + \underbrace{\mathbf{W}_R}_{\text{noise}}\big), \quad (1b)$$

Communication receiver: (1c)

$$\mathbf{Y}_C = \underbrace{\mathbf{HX}}_{\text{signal}} + \underbrace{\mathbf{G}_1\mathbf{PS}\boldsymbol{\Lambda}_1}_{\text{interference}} + \underbrace{\mathbf{W}_C}_{\text{noise}}, \quad (1d)$$

where

- $\mathbf{P}, \mathbf{S}, \boldsymbol{\Omega}$: radar precoder, waveforms, subsampling matrix
- $\mathbf{D} = \sum_{k=1}^{K} \sigma_{\beta_0}^2 \mathbf{v}_t^*(\theta_k)\mathbf{v}_t^T(\theta_k)$
- $\mathbf{C} \triangleq \sum_{k=1}^{K_c} \beta_k^c \mathbf{v}_r(\theta_k^c)\mathbf{v}_t^T(\theta_k^c)$: clutter response matrix
- $\mathbf{X} \triangleq [\mathbf{x}(1), \ldots, \mathbf{x}(L)]$: comm codewords $\mathbf{x}(l) \sim \mathcal{CN}(0, \mathbf{R}_{xl})$
- $\boldsymbol{\Lambda}_1$,$\boldsymbol{\Lambda}_2$: diagonal matrices denoting random phase offsets

The Co-Design Problem

- **Radar SINR:**

$$\text{SINR} = \frac{m\,\mathsf{Tr}\left(\mathbf{P}\mathbf{P}^H\mathbf{D}\right)}{m\,\mathsf{Tr}\left(\mathbf{P}\mathbf{P}^H\mathbf{C}\right) + \sum_{l=1}^{L}\mathsf{Tr}\left(\mathbf{G}_{2l}\mathbf{R}_{xl}\mathbf{G}_{2l}^H\right) + m\sigma_R^2}. \quad (2)$$

Constraints:

- The power budget at the communication transmitter: $\sum_{l=1}^{L}\mathsf{Tr}(\mathbf{R}_{xl}) \leq P_t$,
- The requirement on the average communication rate achieved during the L symbol periods

$$\mathsf{C}_{\mathsf{avg}}(\{\mathbf{R}_{xl}\}) \triangleq \frac{1}{L}\sum_{l=1}^{L}\log_2\left|\mathbf{I} + \mathbf{R}_{\mathsf{Cin}}^{-1}\mathbf{H}\mathbf{R}_{xl}\mathbf{H}^H\right| \geq C \quad (3)$$

$$\mathbf{R}_{\mathsf{Cin}} = \mathbf{G}_1\mathbf{P}\mathbf{P}^H\mathbf{G}_1^H + \sigma_C^2\mathbf{I}.$$

The Co-Design Problem

- Cooperate on estimating $\mathbf{G}_1$, $\mathbf{G}_2$. Share $\mathbf{H}$, $\mathbf{G}_1$, and $\mathbf{G}_2$ with the controller.
- The controller designs $\mathbf{\Phi} = \mathbf{P}\mathbf{P}^H$, $\mathbf{\Omega}$ and $\{\mathbf{R}_{xl}\}$ as

$$\max_{\{\mathbf{R}_{xl}\}\succeq 0, \mathbf{\Phi}\succeq 0, \mathbf{\Omega}} \mathsf{SINR}\left(\{\mathbf{R}_x\}, \mathbf{\Omega}, \mathbf{\Phi}\right),$$

$$\text{s.t.} \quad C_{\mathsf{avg}}(\{\mathbf{R}_{xl}\}, \mathbf{\Phi}) \geq C, \tag{4a}$$

$$\sum_{l=1}^{L} \mathsf{Tr}\left(\mathbf{R}_{xl}\right) \leq P_C, L\mathsf{Tr}\left(\mathbf{\Phi}\right) \leq P_R, \tag{4b}$$

$$\mathbf{\Omega} \text{ is proper} \tag{4c}$$

The Interference Channel

- The interference channel matrix is directly related to the radar location, as seen in the following model [Heath, 2017] [Molisch, 2012]

$$\mathbf{G_2} = \frac{\sqrt{E_x}\lambda_c}{4\pi d\sqrt{M_C^t}}\left(\sqrt{\frac{K}{1+K}}\mathbf{S}_{\mathsf{LoS}} + \sqrt{\frac{1}{1+K}}\mathbf{S}_{\mathsf{NLoS}}\right) \qquad (5)$$

- λ_c: carrier wavelength; E_x: transmit energy; d: the radar distance from the smartphone; K is the Rician factor.
- $\mathbf{S}_{\mathsf{LoS}} = \mathbf{e}_r(\Omega_r)\mathbf{e}_t(\Omega_t)^T$ and $\mathbf{S}_{\mathsf{NLoS}}$ a matrix of i.i.d. $\mathcal{N}_{\mathbb{C}}(0,1)$ entries.
- $\Omega_t = sin(\phi_t)$ and $\Omega_r = sin(\phi_r)$ the angles of incidence of the Line-of-Sight path on the TX and RX steering vectors

$$\mathbf{e}_t(\Omega_t) = \left[1, e^{-j\frac{2\pi\Delta_t}{\lambda_c}\Omega_t}, \ldots, e^{-j(M_C^t-1)\frac{2\pi\Delta_t}{\lambda_c}\Omega_t}\right]^T,$$

$$\mathbf{e}_r(\Omega_r) = \left[1, e^{-j\frac{2\pi\Delta_r}{\lambda_c}\Omega_r}, \ldots, e^{-j(M_R^r-1)\frac{2\pi\Delta_r}{\lambda_c}\Omega_r}\right]^T$$

Security of Spectrum Sharing

[Li and Petropulu, 2017]

- The controller is incorporated into the MIMO radar.
  - This avoids interference during communication with the radar.
  - Also, the controller is a trusted node.
- The controller collects information from the two systems and designs the precoders so that some performance objective is met.
- The computed precoder is passed to the communication system.

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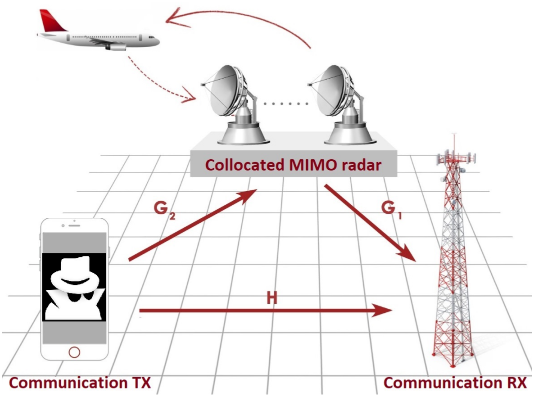
- The controller collects information from the two systems and designs the precoders so that some performance objective is met.
- The computed precoder is passed to the communication system.
- The precoder contains *implicit* information about the radar.

Security Concern

- Can the precoder be used by an adversary to launch an inference attack?



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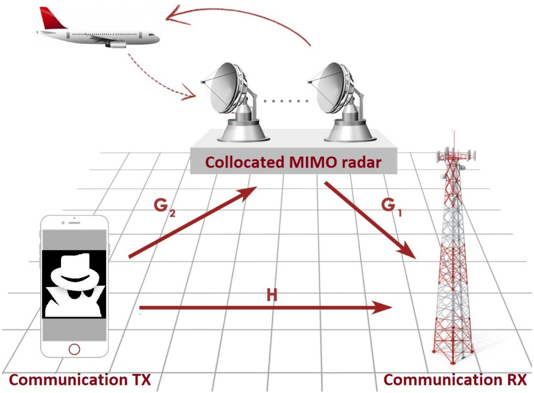

- Can the adversary reverse engineer the precoder matrix to infer the radar location?

Communication System Precoders

- Two precoders are examined here:
  - **Null Space Precoder** - Zero forces the interference at the radar receive antennas

$$\mathbf{P}_n = nullspace(\mathbf{G}_2)$$

    Assumes more comm system TX antennas than radar RX antennas

    [Sodagari et al. 2012, Babaei et. al., 2013, Khawar et. al.]

  - **Optimized Precoder** - Designed to minimize interference at the radar RX, subject to the comm system meeting certain rate and power constraints.

    [Li, Petropulu, Trappe, 2016],[Li, Kumar, and Petropulu, 2016], [Li and Petropulu, 2017]

Outline

Adversary Inference Attack

- Suppose an adversary is operating S independent smartphones, and observes at every point in time $t = 1, \ldots, T$ all precoder matrices $\mathcal{P}^t = \{\mathbf{P}_1^t, \ldots, \mathbf{P}_S^t\}$ sent to the smartphones by the controller.
- For simplicity, each precoder is obtained independently of the others.
- The adversary is not capable of estimating $\mathbf{G}_2$; otherwise it would easily locate the radar.
- The adversary treats the unknown radar location as a random variable R, and attempts to create an estimate of its pdf, p_R, based on the observed precoders sent by the controller.

Optimal Adversary Estimation I

- This can be formulated as a Bayesian inference problem, where the conditional pdf of a sequence of T candidate radar locations given a sequence of T precoders equals

$$p_R\left(R^1,\ldots,R^T|\mathcal{P}^1,\ldots,\mathcal{P}^T\right) = \frac{p_{P|R}\left(\mathcal{P}^1,\ldots,\mathcal{P}^T|R^1,\ldots,R^T\right)}{p_P\left(\mathcal{P}^1,\ldots,\mathcal{P}^T\right)} p_R\left(R^1,\ldots,R^T\right) \tag{6}$$

- $p_{P|R}$ is the probability of the observed precoder matrices given a specific radar location.
- May assume that all candidate locations are equally likely, i.e., the a priori pdf $p_R\left(R^1,\ldots,R^T\right)$ is a constant.

Optimal Adversary Estimation II

- May also assume that the controller assignments are memoryless, i.e.,

$$p_R\left(R^1,\ldots,R^T|\mathcal{P}^1,\ldots,\mathcal{P}^T\right)=\frac{\prod_{t=1}^{T}p_{P|R}\left(\mathcal{P}^t|R^t\right)}{\sum_{\mathcal{R}}\prod_{t=1}^{T}p_{P|R}\left(\mathcal{P}^t|R^t\right)} \tag{7}$$

  $\mathcal{R}$ is he set of all candidate location sequences.
- If the adversary knew $p_{P|R}\left(\mathcal{P}^t|R^t\right)$, it could compute (7) for every possible combination of candidate locations.

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- If the adversary knew $p_{P|R}\left(\mathcal{P}^t|R^t\right)$, it could compute (7) for every possible combination of candidate locations.
- Optimal estimation is computationally prohibitive → use a supervised machine learning approach for radar location estimation.

Machine Learning Estimation

- Adversary divides search area into cells.
- Adversary trains a classifier for every separate cell, using training data and their corresponding labels.
- Features in the classification problem are the precoding matrices, separated into real and imaginary parts, and stacked in a long vector.
- Once training has been completed, the adversary can decide which cell a new precoder corresponds to. This task can be parallelized.

Mutual Information

- One way to quantify the amount of information a precoder reveals about the radar location is via the *Mutual Information (MI)*.
- $R = (R_x, R_y) \sim p(R_x, R_y)$ denote radar coordinates, and $P = [P_1, ..., P_n]^T \sim p\,(P_1, \ldots, P_n)$ the precoder vector.

Mutual Information $I(R; P) \triangleq$

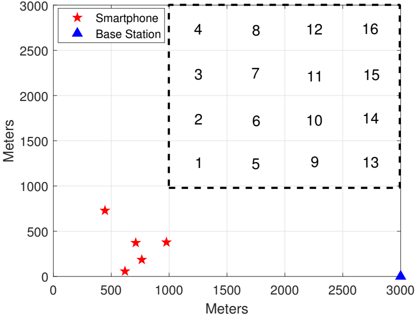
$$\int \cdots \int p(R_x, \ldots, P_n) \log_2 \frac{p(R_x, \ldots, P_n)}{p(R_x, R_y) p\,(P_1, \ldots, P_n)} dR_x \ldots dP_n \quad (8)$$

- MI can be estimated numerically using multi-dimensional histograms.

Outline

Simulation Setup

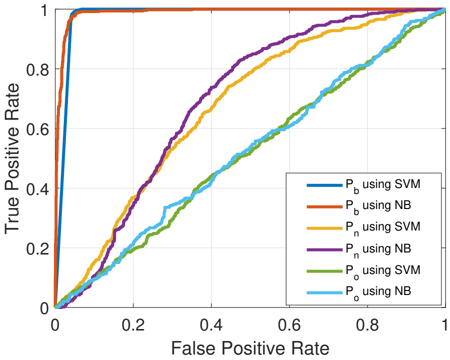
- The adversary will test all cells and make a binary decision on the presence of the radar in a particular cell.
- We assume the adversary is controlling $S = 5$ smartphones.
- The radar has $M_R^r = M_R^t = 6$ antennas and the communication system has $M_C^t = M_C^r = 8$ antennas.



Simulation Setup

- Baseline approach $(\mathbf{P}_b) \rightarrow$ the adversary observes $\mathbf{G}_2$.
- Three separate balanced training sets $\mathcal{L}_b^c$, $\mathcal{L}_n^c$, $\mathcal{L}_o^c$, of 6000 samples each were created for cell $c = 4$, for the cases where the adversary observes $\mathbf{P}_b$, $\mathbf{P}_n$, and $\mathbf{P}_o$, respectively.
- A separate test set $\mathcal{T}^c$ for $c = 4$ was created, consisting of 2375 samples; 500 samples correspond to precoders for radar locations in $c = 4$, and $1,875$ samples for the radar in all other cells (125 samples for each $c \neq 4$.
- To avoid over-fitting, the radar locations used for training were different that those used in testing.
- For training we used the Support Vector Machine (SVM) and Naive Bayes (NB) classifiers (Matlab functions *fitcsvm* and *fitcnb*, respectively).

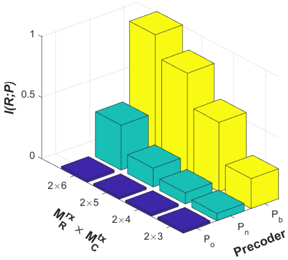
Simulation Setup



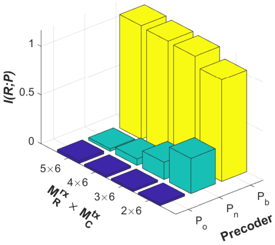
- ROC for cell $c = 4$
- $\mathbf{P}_b$ results in almost perfect radar location prediction.
- Using $\mathbf{P}_o$ results in a random adversary guess $\rightarrow$ $\mathbf{P}_o$ a better option in protecting the radar privacy.

Mutual Information

- Numerically computed mutual information for all assumed precoders.
- Depending on precoder, the bins of the multi-dimensional histogram where created from the positive samples of $\mathcal{L}_b^c$, $\mathcal{L}_n^c$, or $\mathcal{L}_o^c$, using the K-means clustering algorithm.



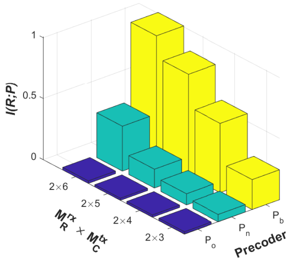
(a)



(b)

Mutual Information

- Notice that $I(R; P_o) < I(R; P_n) < I(R; P_b) \rightarrow$ greater reduction in the uncertainty of R when observing P_b than when observing P_o.
- In other words, $\mathbf{P}_b$ reveals the most information about a radar location while $\mathbf{P}_o$ the least.



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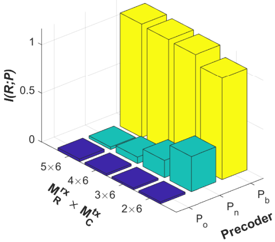

(b)

Mutual Information

- For $\mathbf{P}_b$ or $\mathbf{P}_n$, an increase in the # of transmit antennas at the communication system results in an increase to the mutual information $\rightarrow$ respective increase in the column space of $\mathbf{P}_b$ directly affects the size of $\mathbf{P}_n$ as well.
- The value of $I(R; P_o)$ is very small $\rightarrow$ R and P_o are close to being independent, with most of the radar information being suppressed in the optimized precoder.
- $\mathbf{P}_n$ is only a function of $\mathbf{G}_2$ but $\mathbf{P}_o$ is additionally a function of $\mathbf{H}, \mathbf{G}_1$.
- $\mathbf{P}_o$ is obtained as the solution of a constrained optimization problem $\rightarrow$ contribution of $\mathbf{G}_1$ to the final solution less transparent and $\mathbf{H}$ by definition has no information regarding the radar position.
- The optimal precoder $\mathbf{P}_o$ seems to be better for the radar privacy but involves more computational complexity.

Outline

- We examined the extent to which the adversary can infer radar location information from the communication system precoder matrix, using a machine learning based inference attack.
- Depending on the used precoder scheme, our simulations indicated that this was indeed possible, a result further supported by our estimation of the mutual information between the precoder matrix and radar location.

Future work

The precoder $\mathbf{P} = \sqrt{\mathbf{R}_{xl}}$ is the solution to:

$$\begin{aligned}
\min_{\mathbf{R}_{xl}} \quad & \sum_{l=1}^{L} Tr(\mathbf{G}_2 \mathbf{R}_{xl} \mathbf{G}_2^H) \\
\text{s.t.} \quad & \sum_{l=1}^{L} Tr(\mathbf{R}_{xl}) \leq P_C \quad \text{(restricts comm. TX antenna power)} \\
& \frac{1}{L} \sum_{l=1}^{L} \log_2 |\mathbf{I} + \mathbf{R}_{wl}^{-1} \mathbf{H} \mathbf{R}_{xl} \mathbf{H}^H| \geq C \quad \text{(restricts comm. average capaci} \\
& I(\mathbf{R}; \mathbf{P}) \leq M
\end{aligned}$$

where $\mathbf{R}_{xl}$ is the transmit covariance matrix, M an accepted scalar value for which we assume privacy is achieved.

Thank you!
Questions?

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