Ultra-Wideband (UWB) Wireless Communications

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Outline

- Introduction
- UWB Principles
- UWB Propagation Mechanisms—Time Domain
- UWB based IEEE 802.15.3a
  - Multi-band OFDM
- Per-Path Pulse Distortion
- Physics-based System Modeling
- Conclusion
Mobile Devices Market Segmentation

- Modules - Embedded Apps
- Telematics / Telemetry
- Add-On Devices
- Data Devices w/ Integral Wireless
- Business / Smart Phones
- Basic Phones

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Nokia 3330
Add-On Devices
Business / Smart Phones

Ericsson R380
PDQ
Smart Phone

RIM Blackberry
HandSpring Visor, Spring Board Modules

HP Jornada 720
Handspring 720

Greater Multi-Media Capability
Larger Displays / Touch-Screens and Keyboards
Multi Wireless Modes & Generally Higher Data Rates
UWB Applications

- High-data-rate wireless personal area network (HDR-WPAN)
- Intelligent wireless area network (IWAN)
- Wireless body area network (WBAN)
- Sensor, positioning, and identification network (SPIN)
- Outdoor peer-to-peer network (OPPN)

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UWB Applications (IEEE 802.15.3a)

- WPAN (range<10m) for multimedia digital stream (110-480 Mbps)
- Home Entertainment Devices
- Home Network Devices
- PC Enterprise Business Market

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UWB Communications & Sensor Networks

Applications
- Remote surveillance, threat detection
- Video to the foxhole/battlefield
- High-resolution location services

Key Technologies
- Ultra-wide band systems
- Mobile, adhoc networks
- Data fusion / synthesis

Open Research Issues
- System and protocol design
- Analysis, performance modeling
- Test-bed development / trials

Environments
- Real-time
- Distributed
- Dynamic
- Hostile

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What Is Ultra-Wideband (UWB)?

- **Definition (In radar, etc)**

  \[ \frac{f_u - f_l}{f_u + f_l} \geq 0.25 = 25\% \]

  Where:
  - \( f_u \) = upper 10 dB down point
  - \( f_l \) = lower 10 dB down point

- Or greater than **500 MHz (FCC Feb 2002)**

- At FCC Part 15 powers (a few tens of *microwatts* total - across several GHz), cannot be reliably measured below 10 dB down points
7.5 GHz UWB Spectrum Allocated by FCC 02/2003

Source: IBM Research

- Conventional carrier modulation
- Direct sequence spread spectrum
- Ultra-wideband

Note: Drawing not to scale

Frequency (GHz)

Power spectral density (W/Hz)

Bandwidth (Hz)

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FCC Feb. 2002 Ruling

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Time Modulated Ultra-Wideband—An Example

- Not a sinewave, but millions of pulses per second

- Time coded to make noise-like
  - Channelization
  - Anti-jam
  - Smooths spectrum

- Pulse position modulation

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UWB with PPM—An Example

Transmitted Signal Bursts

$T_f$  
$T_c$

d = data sequence, addition binary pulse position modulation

time frame location determined by PN code sequence

$\omega(t) = \sum_j \omega(t - jT_f - c_jT_c - d_{[j/N_{rep}]})$

The frame time $T_f$

the chip time ($T_c$)

The $c_j$ represents a distinctive time-hopping sequence pattern

d = data sequence, addition binary pulse position modulation

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UWB Impulse Radio (simplified)—Example

Radio Frequency Power Spectra

Channel=Filter

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1 μW

1 GHz

2 GHz

3 GHz

0

Radio Frequency Power Spectra

1 ns
(time)

1 foot
(space)
Propagation Measurement

650 MHz Impulse at 12 meters in an Office Building

650 Impulse Signal at 3 meters in an Office Building

Source: Robert Schultz, USC
Physics of UWB scattering - Multipath Fading Immunity Benefits

Wide bandwidth means signal and correlator outputs can be short in time

Result is that multipath components can be separately resolved ➞ **time domain paradigm shift**

Each component can have full bandwidth

Narrowband systems can confuse multipath with attenuation

The two top charts are time & frequency duals

Fading immunity means channel model closely follows $R^2$ (free space) rather than $R^{3.5}$ or $R^4$

Leads to robust in-building operation

Bottom chart shows actual signal strength measured in a typical office environment (blue) along with reference $R^{3.5}$ (red) and $R^2$ (green) traces

**Multipath fading immune**

**Exceeds specified delay spread**

**Reduces Required Link Budget**
Information Theory Benefits

Shannon’s Equation

\[ C = B \log \left( 1 + \frac{S}{N} \right) = B \log \left( 1 + \frac{P_0 B}{KTB} \right) = B \log \left( 1 + \frac{P_0}{KT} \right) \]

Regulatory limits provide \( P_0 \) (Watts/Hz) for UWB

High order modulation

Allows data rate capacity \( C \) to be larger than channel bandwidth \( B \)

BUT requires high SNR and allows the trades data-rate for range or power at an unfavorable \( \log \) function with power.

Low order modulation and \( B \gg C \)

*linearly* trades data-rate for range or power
allows software controlled integration-gain to push bandwidth into the SNR
Allows simple, inexpensive, low-linearity, radio implementation

Large BW \( \Rightarrow \) high capacity with low order modulation & low power

Data rate is proportional channel bandwidth \( B \)

Bandwidth comes from IC process in the proposed solution

Moore’s Law Radio

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Channel Measurement Test Setup

- **Transmit Ant**
  - TDC SQ
  - 10 ns/div
  - 350 Averages

- **Recv Ant & Mount**
  - Miteq
  - 30 dB @ 4 GHz
  - ≈ 0.4 nsec delay
  - Preamp NF = 2.2

- **DSO**
  - HP54750A
  - Ch.1
  - Trig
  - Ch.2

- **Trigger Cable**
  - ≈ 50 ft.
  - RG-223/U
  - = 21 dB @ 4 GHz
  - = 78 nsec delay

- **High Pass Filter, ISM, & PCS Notch**
  - 4.5" of Semi Rigid
  - ≈ 1.0 nsec delay

- **Male to Male SMA**
  - ≈ 1 nsec delay

- **HP8495B**
  - 0-70 dB, 10 dB Step Variable Attenuator
  - BC5 = 2 ft.
  - RG-223/U
  - -1.3 dB @ 4 GHz
  - ≈ 3 nsec delay

- **HP8494B**
  - 0-11 dB, 1 dB Step Variable Attenuator
  - BC5 = 2 ft.
  - RG-223/U
  - -1.3 dB @ 4 GHz
  - ≈ 3 nsec delay

- **HP54750A**
  - Ch.1
  - Trig
  - Ch.2

- **Trigger Cable**
  - ≈ 50 ft.
  - RG-223/U
  - = 21 dB @ 4 GHz
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- **Miteq**
  - 30 dB @ 4 GHz
  - ≈ 0.4 nsec delay
  - Preamp NF = 2.2

- **+15 Vdc P.S.**
  - Calex CM1.15.400-115

- **22 nsec Delay Line**
  - HP54008A
  - ≈ 2 dB @ 4 GHz

- **BC1 = 50 ft.**
  - RG-223/U
  - ≈ 21 dB @ 4 GHz
  - ≈ 78 nsec delay

- **BC2 = 3 ft.**
  - RG-223/U
  - = -2.0 dB @ 4 GHz
  - = 4.5 nsec delay

- **Trigger Cable**
  - ≈ 50 ft.
  - RG-223/U
  - = 21 dB @ 4 GHz
  - = 78 nsec delay

- **High Pass Filter, ISM, & PCS Notch**
  - 4.5" of Semi Rigid
  - ≈ 1.0 nsec delay

- **Male to Male SMA**
  - ≈ 1 nsec delay

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- **Male to Male SMA**
  - ≈ 1 nsec delay
Transmitted and Received Pulses

Transmitted voltage waveform measured at coax input to the horn

Received waveform shows a single time differentiation

- Small Antenna gain

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Representative Measurements II

<table>
<thead>
<tr>
<th></th>
<th>Blocked LoS</th>
<th>Hold Rcvd Clear LoS</th>
<th>Hold Rcvd Blkd LoS</th>
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<tbody>
<tr>
<td>50 ns</td>
<td></td>
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<td></td>
</tr>
<tr>
<td>1 ns</td>
<td></td>
<td></td>
<td></td>
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</tbody>
</table>

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IEEE 802.15.3a—A Review

- What is going on?
- Technical Issues of Proposals
Why UWB and why spectrum agility?

**Why UWB for IEEE 802.15.3a?**
- UWB technology is uniquely suited for high-rate, short range access
  - Theoretical advantages for approaching high rates by scaling bandwidth
  - Newly allocated unlicensed spectrum (7.5 GHz) that does not take away from other narrowband systems (licensed or unlicensed)
  - CMOS implementations now possible at these higher frequencies ➔ All CMOS architecture

**Why spectrum agility for a UWB solution?**
- Just because the FCC allows UWB to transmit on top of other services does not mean we should!
  - Government regulations should be broader than industry requirements
- Spectrum usage and interference environment changes by country location, within a local usage area, and over time
  - Enable adaptive detection and avoidance strategies for better coexistence and possible non-contiguous spectrum allocations for flexible regulations in future
- Allow for simple backward compatibility and future scalability

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Flexible Spectrum Use

- Center frequencies chosen for **ease of implementation**
- 440 MHz band separation for **improved flexibility**
- ~538 MHz wide bands to best utilize spectrum

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Why did 10 Companies Propose Multi-Band Solutions in March 2003?

Some of the reasons include:

- **Spectrum Flexibility / Agility**
  - Regulatory regimes may lack large contiguous spectrum allocations
  - Spectrum agility may ease coexistence with existing services

- **Energy collected per RAKE finger scales with longer pulse widths used**
  - Fewer RAKE fingers

- **Reduced bandwidth after down-conversion mixer reduces power consumption and linearity requirements of receiver**

- **Fully digital solution for the signal processing is more feasible than a single band solution for the same occupied bandwidth**

- **Transmitter pulse shaping made easier**
  - Longer pulses easier to synthesize & less distorted by IC package & antenna properties

- **Have the ability to utilize an FDMA mode for severe near-far scenarios**
Most of the Multi-Band Proposals in March 03’ used Pulses, What Happened?

- Energy collection under severe multipath (CM3, CM4) required improvement

- We needed a computationally efficient method of multipath combining
  - Parallel receivers? Infinite RAKE? OFDM?

- OFDM in each sub-band was selected as a successor to the pulsed multi-band approaches
Why are 34+ Companies Now Supporting the Multi-band OFDM Approach?

- Multi-band OFDM kept the unique Multi-Band benefits **and** solved the energy collection problem very elegantly
- Feasibility studies of FFT and Viterbi cores showed encouraging numbers for gate-count and power consumption
- Multi-band OFDM suitable for CMOS implementation (**all components**)
- Antenna and pre-select filter are easier to design (can possibly use off-the-shelf components)
- Low cost + low power + CMOS integrated solution = early market adoption
- Scalability:
  - Digital section complexity/power scales with improvements in technology nodes (**Moore’s Law**).
  - Analog section complexity/power scales slowly with technology node
- Much more can be said in detail about the Multi-band OFDM PHY performance, but first we should review our proposal…

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Overview of OFDM

- OFDM was invented more than 40 years ago
  - Adopted by numerous standards effort:
    » Asymmetric Digital Subscriber Line (ADSL) services.
    » IEEE 802.11a/g; IEEE 802.16a
    » Digital Audio Broadcast (DAB); Home Plug
    » Digital Terrestrial Television Broadcast: DVD in Europe, ISDB in Japan
- OFDM is also being considered for 4G, IEEE 802.11n and 802.20

- OFDM is spectrally efficient.
  - IFFT/FFT operation ensures that sub-carriers do not interfere with each other
- OFDM has an inherent robustness against narrowband interference.
  - Narrowband interference will affect at most a couple of tones.
  - Information from the affected tones can be erased and recovered via the forward error correction (FEC) codes
- OFDM has excellent robustness in multi-path environments.
  - Cyclic prefix preserves orthogonality between sub-carriers.
  - Cyclic prefix allows the receiver to capture multi-path energy more efficiently
Overview of Multi-Band OFDM

- Basic idea: divide spectrum into several 528 MHz bands

- Information is transmitted using OFDM modulation on each band
  - OFDM carriers are efficiently generated using an 128-point IFFT/FFT
  - Internal precision is reduced by limiting the constellation size to QPSK

- Information bits are interleaved across all bands to exploit frequency diversity and provide robustness against multi-path and interference

- 60.6 ns prefix provides robustness against multi-path even in the worst channel environments

- 9.5 ns guard interval provides sufficient time for switching between bands

- Solution is very scalable and flexible
  - Data rates, power scaling, frequency scaling, complexity scaling
Proposal for IEEE 802.15.3a

Multi-band OFDM: TX Architecture

- Block diagram of an example TX architecture:

- Architecture is similar to that of a conventional and proven OFDM system. Can leverage existing OFDM solutions for the development of the Multi-band OFDM physical layer.

- For a given superframe, the time-frequency code is specified in the beacon by the PNC. The time-frequency code is changed from one superframe to another in order to randomize multi-piconet interference.
# Multi-band OFDM System Parameters

- System parameters for mandatory and optional data rates:

<table>
<thead>
<tr>
<th></th>
<th>55 Mbps*</th>
<th>80 Mbps**</th>
<th>110 Mbps*</th>
<th>160 Mbps**</th>
<th>200 Mbps*</th>
<th>320 Mbps**</th>
<th>480 Mbps**</th>
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</thead>
<tbody>
<tr>
<td><strong>Modulation/Constellation</strong></td>
<td>OFDM/QPSK</td>
<td>OFDM/QPSK</td>
<td>OFDM/QPSK</td>
<td>OFDM/QPSK</td>
<td>OFDM/QPSK</td>
<td>OFDM/QPSK</td>
<td>OFDM/QPSK</td>
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<tr>
<td><strong>FFT Size</strong></td>
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<td>128</td>
<td>128</td>
<td>128</td>
<td>128</td>
<td>128</td>
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<tr>
<td><strong>Coding Rate (K=7)</strong></td>
<td>R = 11/32</td>
<td>R = 1/2</td>
<td>R = 11/32</td>
<td>R = 1/2</td>
<td>R = 5/8</td>
<td>R = 1/2</td>
<td>R = 3/4</td>
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<tr>
<td><strong>Spreading Rate</strong></td>
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<td>2</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td><strong>Information Tones</strong></td>
<td>25</td>
<td>25</td>
<td>50</td>
<td>50</td>
<td>50</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td><strong>Data Tones</strong></td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td><strong>Info. Length</strong></td>
<td>242.4 ns</td>
<td>242.4 ns</td>
<td>242.4 ns</td>
<td>242.4 ns</td>
<td>242.4 ns</td>
<td>242.4 ns</td>
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</tr>
<tr>
<td><strong>Cyclic Prefix</strong></td>
<td>60.6 ns</td>
<td>60.6 ns</td>
<td>60.6 ns</td>
<td>60.6 ns</td>
<td>60.6 ns</td>
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<tr>
<td><strong>Guard Interval</strong></td>
<td>9.5 ns</td>
<td>9.5 ns</td>
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<td>9.5 ns</td>
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<tr>
<td><strong>Symbol Length</strong></td>
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<td>312.5 ns</td>
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<tr>
<td><strong>Channel Bit Rate</strong></td>
<td>640 Mbps</td>
<td>640 Mbps</td>
<td>640 Mbps</td>
<td>640 Mbps</td>
<td>640 Mbps</td>
<td>640 Mbps</td>
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</tr>
<tr>
<td><strong>Multi-path Tolerance</strong></td>
<td>60.6 ns</td>
<td>60.6 ns</td>
<td>60.6 ns</td>
<td>60.6 ns</td>
<td>60.6 ns</td>
<td>60.6 ns</td>
<td>60.6 ns</td>
</tr>
</tbody>
</table>

* Mandatory information data rate, ** Optional information data rate
Per-Path Pulse Distortion– Physics-based Modeling

\[(\nabla^2 - \frac{1}{c^2} \frac{\partial^2}{\partial t^2})E(t,t';r,r') = -\delta(t-t')\delta(r-r')\]

\[(\nabla^2 + k^2)E(k,r,r') = \delta(r-r')\]

\[\alpha_{n} = -\frac{1}{2} \quad \text{for a single edge diffraction} \]

Multiple diffraction must be included!

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[Qiu, 1995]

UTD/MOM
Turin’s Model
[Since 1956]

Qiu, Ph.D. Thesis
[1995]

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Concept of UWB Pulse Distortion due to Diffraction

\[ h(\tau) = \sum_{n=1}^{N_{GO}} A_n \delta(\tau - \tau_n) + \sum_{n=1}^{N_{GD}} B_n R_n(\tau) \otimes \delta(\tau - \tau_n) + \sum_{n=1}^{N_{GTD}} C_n g_n(\tau) \otimes \delta(\tau - \tau_n) + \sum_{n=1}^{N_{GDO,GTD}} D_n [R_n(\tau) \otimes g_n(\tau)] \delta(\tau - \tau_n) \]

UWB pulse distortion is a physical phenomenon !!!

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Waveform Distortion can be Modeled as the Singularity of Wavefront for a Ray

\[ h_n(\tau) = \begin{cases} 
\xi(\tau_\alpha - \tau) \sum_{n=0}^{\infty} \frac{C_n}{n!} (\tau_\alpha - \tau)^n, & \tau < \tau_\alpha \\
\eta(\tau_\alpha - \tau) \sum_{n=0}^{\infty} \frac{D_n}{n!} (\tau_\alpha - \tau)^n, & \tau > \tau_\alpha 
\end{cases} \]

\[ H_n(\omega) = \sum_{n=0}^{\infty} \left\{ \frac{D_n}{n!} \frac{1}{(j\omega)^n} \int_0^\infty \eta\left(\frac{t}{j\omega}\right) t^n e^{-t} dt - \frac{C_n}{n!} \frac{1}{(-j\omega)^n} \int_0^\infty \xi\left(\frac{t}{-j\omega}\right) t^n e^{-t} dt \right\} \]

- The impulse responses of localized scattering centers in a generalized ray can be modeled as the early-time responses in the time domain or asympotic approximation of time-harmonic fields in the FD!
- (Kline 1956)
Exact Solution—UWB Diffraction by Half-Plane

\[ u = u_1 \pm u_2 = A_0 e^{jkr \cos(\theta - \varphi)} F(\sqrt{2kr \cos(\theta - \varphi)}) \pm A_0 e^{jkr \cos(\theta + \varphi)} F(\sqrt{2kr \cos(\theta + \varphi)}) \]

\[ h(\tau) \triangleq \mathcal{L}^{-1} \left( \frac{u(\omega)}{u_0} \right) = \frac{\sqrt{2r/c}}{2\pi} \left[ \frac{\cos \frac{1}{2} (\theta - \varphi)}{\tau + \frac{r}{c} \cos(\theta - \varphi)} - \frac{\cos \frac{1}{2} (\theta + \varphi)}{\tau + \frac{r}{c} \cos(\theta + \varphi)} \right] \frac{1}{\sqrt{\tau - r/c}} \sim \tau^{-1/2} \otimes \delta(\tau - r/c) \]

At the wave front a PEC edge has a singularity of \( \tau^{\alpha} \quad \alpha = -1/2 \)
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System Performance—Optimum Receiver

\[
P_e = Q \left( \sqrt{\frac{\lambda d^2(\tau_0)}{2}} \right), \quad d^2(\tau_0) = 1 - R_{\tilde{p}(t)\tilde{p}(t-\tau_0)}(\tau_0)
\]

\[
R_{\tilde{p}(t)\tilde{p}(t-\tau_0)}(\tau_0) = \frac{1}{E_{\tilde{p}}} \int_{-\infty}^{\infty} \tilde{p}(t) \tilde{p}(t - \tau_0) dt
\]

\[
\tilde{p}(t) = p_{TX}(t) * h(t), \quad h(t) = \sum_{l=0}^{L-1} a_l h_l(t) * \delta(t - \tau_l)
\]

\[
R_{\tilde{p}(t)\tilde{p}(t-\tau_0)}(\tau_0) = R_{pp}(t) * \left( h(t) * h(-t) \right) \delta(t - \tau_0)
\]
Diffraction-Based Pulse Shape Transform

\[ d(t) \text{ and } v(t) \]

- \( \alpha = -1: 0.25: 0 \) (bottom to top)
- \( \alpha = 0 \) \( \Rightarrow \) Incident Waveform
- Red dashed Template Pulse \( v(t) \)

\[ t \text{ (ns)} \]

0 \( \Rightarrow \) 1
Summary

- UWB is one of the most promising technologies
  - 7.5 GHz unlicensed spectrum from 3.1-10.6 GHz
  - Volume products will be shipped in 3-4 years

- UWB is good for both short-range (10-30m) and long-range (100-1000m)

- Per path pulse distortion in a UWB channel is one of the major potential problems in system design
  - Experimental measurements needed
  - Physics-based system modeling

- UWB MIMO is good for extending UWB range
Thank You!

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