

Adaptive WPT Beam Time Allocation via Queue-Length Feedback for Indoor SWIPT Systems

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Abstract—This paper proposes an adaptive scheduling protocol for battery-free Internet-of-things (IoT) sensor networks, where a multi-antenna transmitter delivers radio frequency (RF) energy via beamforming while simultaneously collecting data. We introduce a *harvest-then-transmit (HTT)* frame structure that partitions each frame into per-beam subframes, each comprising a wireless power transfer (WPT) window immediately followed by a wireless information transfer (WIT) window, thereby enabling independent WPT duration control for each beam. To address uneven queue lengths across subframes, we propose a *queue-length-proportional WPT time allocation* that dynamically adjusts beam durations based on per-beam queue information available at the gateway (GW). Two methods of obtaining the queue information are considered: explicit feedback in which each node appends a b -bit quantized queue length to its packet, and a zero-overhead scheme in which the GW infers per-node queue lengths from a sliding window of received-packet history. The proposed scheme improves delivery ratio by 4.3pp over non-adaptive equal-time beamforming, reaching 99.3% with full queue feedback, 98.9% with $b = 2$ bits of feedback, and 97.6% with zero-overhead GW-side queue estimation.

Index Terms—wireless power transfer, beamforming, harvest-then-transmit, packet scheduling, feedback quantization

I. INTRODUCTION

Wireless sensor networks (WSNs) have become a foundational technology for Internet-of-things (IoT) applications, enabling pervasive monitoring of physical environments through densely deployed, low-cost sensor nodes [1]. A longstanding bottleneck in large-scale WSN deployments is the reliance on electrochemical batteries, which limit node lifetime, impose maintenance overhead, and hinder deployment in inaccessible locations [2]. Wireless power transfer (WPT) via radio frequency (RF) energy harvesting has emerged as a promising approach to eliminate batteries entirely, allowing sensor nodes to operate by scavenging dedicated RF signals [3].

Simultaneous wireless information and power transfer (SWIPT) integrates energy delivery and data collection into a single coordinated system, in which a gateway (GW) transmits RF energy to power terminals while simultaneously receiving their data packets [4], [5]. Equipping the GW with multiple antennas further increases the spatial efficiency of energy delivery: beamforming concentrates RF power toward targeted terminals rather than radiating uniformly, alleviating the severe

path loss that limits single-antenna WPT [6]. In an indoor deployment, a set of fixed beams steered to predefined directions can cover the room while keeping the transmitter design simple and channel acquisition lightweight.

Existing studies jointly optimize beam weights or WPT/wireless information transfer (WIT) time allocation [6]–[8], but formulate centralized problems assuming instantaneous channel state information (CSI) and full network state knowledge. Under uniform beam scheduling, terminals in weak-channel zones accumulate packet queues faster than they drain; conveying such queue-length information from microjoule-budget terminals incurs non-trivial cost. Recent studies model WPT scheduling as an Markov decision process (MDP) [9] or via reinforcement learning (RL) [10] to incorporate queue dynamics, but require per-terminal battery and queue state whose dimensionality grows with network size. Our objective is instead a lightweight scheme: a simple proportional update driven by minimal queue feedback, without centralized optimization or learning.

In this paper, we develop such an autonomous scheme for an indoor beamforming SWIPT system. We propose a *per-beam harvest-then-transmit (HTT)* frame structure in which the WPT window of each beam immediately precedes its dedicated WIT window, enabling terminals to exploit freshly harvested energy within the same frame. Within this structure, we develop a *queue-length-proportional WPT time allocation* algorithm in which the GW adjusts each beam's WPT duration in proportion to the aggregated queue lengths of its assigned terminals, redirecting energy toward backlogged beams to prevent energy starvation without centralized optimization. We then characterize how much terminal-side information the GW needs: at one extreme, the GW can accurately reconstruct terminal queue states from its own reception history alone, eliminating uplink reporting entirely; we also identify the minimum number of feedback bits per packet sufficient for near-optimal allocation when explicit reporting is preferred.

The rest of this paper is organized as follows. Section II describes the system model. Section III presents the proposed per-beam HTT protocol, queue-length-proportional WPT time allocation, and GW-side queue estimation. Section IV presents simulation results, and Section V concludes the paper.

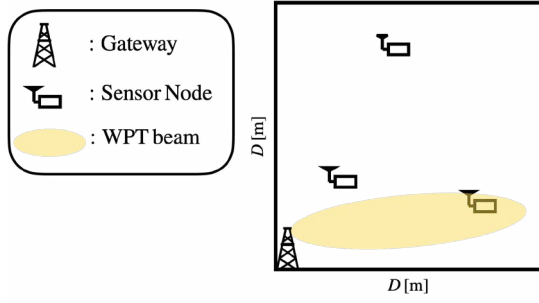


Fig. 1. Indoor SWIPT environment.

II. SYSTEM MODEL

This paper considers an indoor environment as illustrated in Fig. 1. In a $D \times D$ [m²] room, N battery-free sensor nodes are randomly deployed, each maintaining a minimum distance $d_{\min}$ from a GW. The GW is equipped with an M -element uniform linear array (ULA) and is placed at one corner of the room. It serves as both a wireless power transmitter and a data packet receiver. The system operates in discrete frames, each consisting of a WPT phase followed by a WIT phase. During the WPT phase, the GW delivers RF energy via ULA beams steered in predefined fixed directions. Subsequently, the nodes transmit their data packets to the GW in the WIT phase.

A. Beamforming and Channel Model

The ULA broadside is directed at $\varphi_b = \pi/4$ [rad], providing symmetric coverage across the room's angular sector $[0^\circ, 90^\circ]$. The GW steers beams toward S discrete directions in this range, with the s -th beam center at

$$\theta_s = \frac{(2s-1)\pi}{4S}, \quad s = 1, \dots, S. \quad (1)$$

Let θ_k denote the angle from the GW to node k in room coordinates, and define the broadside-relative angles $\tilde{\theta}_k = \theta_k - \varphi_b$ and $\tilde{\theta}_s = \theta_s - \varphi_b$. Let $G(\tilde{\theta}_k; \tilde{\theta}_s)$ denote the array gain of the ULA with half-wavelength element spacing, evaluated at $\tilde{\theta}_k$ when steered to $\tilde{\theta}_s$.

The large-scale path gain from the GW to node k at distance d_k is modeled as

$$\beta_k = G_0 \left(\frac{d_k}{d_0} \right)^{-\alpha}, \quad (2)$$

where α is the path-loss exponent, d_0 is a reference distance, and $G_0 = \left(\frac{\lambda}{4\pi d_0} \right)^2$ is the free-space path gain at d_0 . The channel is modeled as quasi-static large-scale path loss with no small-scale fading.

B. Energy Harvesting Model

In each frame, the GW radiates with total power P_A [W]. The beam durations satisfy $\sum_{s=1}^S t_{\text{wpt},s} = T_{\text{wpt}}$, where T_{wpt} [s] is the total WPT duration per frame. When beam s is active for duration $t_{\text{wpt},s}$ [s], the energy harvested by node k is

$$E_{k,s}^{\text{wpt}} = \zeta P_A G(\tilde{\theta}_k; \tilde{\theta}_s) \beta_k t_{\text{wpt},s}, \quad (3)$$

where $\zeta \in (0, 1]$ is the rectification efficiency, modeled as a constant independent of the input power level [11]. More accurate non-linear rectifier models [12] are left for future work. Let $E_k^{(f)}$ [J] denote the stored energy of node k at the beginning of frame f . The energy carried over to frame $f+1$ is

$$E_k^{(f+1)} = E_k^{(f)} + \sum_{s=1}^S E_{k,s}^{\text{wpt}} - E_k^{\text{used},(f)}, \quad (4)$$

where the superscript (f) denotes the frame index and $E_k^{\text{used},(f)} \geq 0$ [J] is the energy consumed for carrier sense and data transmission in frame f .

C. WIT Model

Each node generates one data packet per frame and maintains a first-in first-out (FIFO) packet queue of maximum length $Q_{\max}$. When the queue is full, the oldest packet is discarded to make room for the newly generated one, following a drop-head policy; this ensures that buffered data never becomes older than $Q_{\max}$ frames.

Before transmitting, a node performs carrier sense (CS) up to $C_{\max}$ times to avoid collisions; if the channel is sensed idle in any attempt, the node transmits immediately, and if all $C_{\max}$ attempts find the channel busy, the node transmits anyway at the end of the last back-off, accepting a possible collision rather than deferring to the next frame. The energy cost of each CS attempt is E_{cs} [J], and the total energy required to transmit n packets is

$$E_{\text{tx}}(n) = E_{\text{ovhd}} + n E_{\text{pkt}}, \quad (5)$$

where E_{ovhd} [J] is the fixed overhead energy (preamble, header) and E_{pkt} [J] is the energy per payload packet. Terminal k attempts transmission only if its stored energy $E_k^{(f)}$ meets the threshold $E_{\text{th}} = E_{\text{tx}}(1) + E_{\text{cs}}$, which ensures sufficient energy for at least one CS attempt and one packet. When this condition is satisfied and carrier sense succeeds, the node transmits $\min(q_k^{(f)}, A_{\max})$ packets, where $q_k^{(f)}$ is the queue length at the time of transmission and $A_{\max}$ is the maximum aggregation count.

Packets that collide are discarded without retransmission. The delivery delay of a packet is defined as the number of frames elapsed from its generation to successful reception at the GW.

Each WIT window begins with a guard interval τ_{det} to allow nodes to detect the end of the WPT phase. The effective WIT window per beam is thus

$$T_{\text{wit,eff}} = \frac{T_{\text{wit}}}{S} - \tau_{\text{det}}, \quad (6)$$

where T_{wit} [s] is the total WIT duration per frame. For example, when $\tau_{\text{det}} = 1$ [ms] and $T_{\text{wit}}/S = 12.5$ [ms] [13], the effective duration can be calculated accordingly.

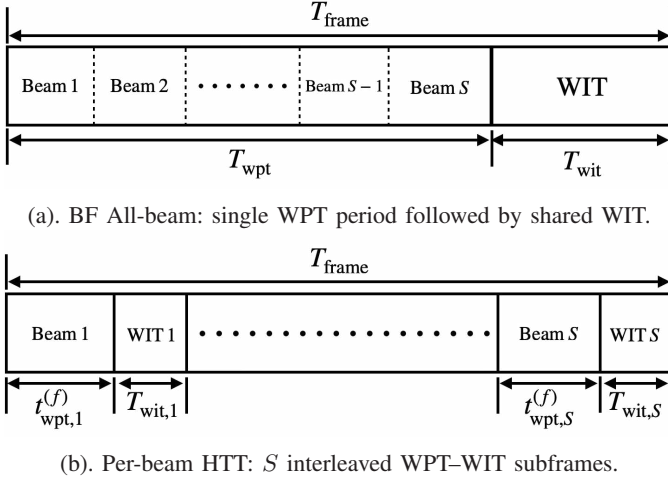


Fig. 2. Frame structures.

III. PROPOSED SCHEME

The proposed scheme is built on a per-beam HTT frame structure that enables independent control of each beam's WPT duration, on top of which the GW performs a queue-length-proportional WPT time allocation. To obtain the per-beam queue information that drives this allocation, we consider two alternatives: explicit b -bit feedback in which each node appends a quantized queue length to its packet, and a zero-overhead GW-side estimation that infers per-node queue lengths from the GW's reception history alone. The two alternatives offer a tradeoff between uplink overhead and allocation accuracy.

A. Per-Beam Harvest-Then-Transmit Frame Structure

The proposed scheme adopts a per-beam HTT frame structure, illustrated in Fig. 2b. In the conventional BF All-beam scheme (Fig. 2a), all S beams are activated during a single WPT period, followed by a shared WIT window. As shown in Fig. 2b, the per-beam HTT structure divides a frame of duration $T = T_{\text{wpt}} + T_{\text{wit}}$ into S sequential subframes; in subframe s of frame f , the GW radiates beam s for a WPT duration $t_{\text{wpt},s}^{(f)}$, followed by a WIT window of duration $T_{\text{wit},s} = T_{\text{wit}}/S$ dedicated to subframe s . Within that WIT window, any node that has not yet transmitted in the current frame may attempt carrier sense and transmit. The GW attributes each node's queue demand to the beam whose WIT window carried the node's most recent packet, because each WIT window is exclusive to a single beam; this attribution is updated implicitly on each successful reception, requiring no dedicated control signaling. Note that only the per-beam WPT durations $t_{\text{wpt},s}^{(f)}$ are adapted across frames; each beam's WIT window length is fixed to T_{wit}/S and is never varied.

B. Queue-Length-Proportional WPT Time Allocation

An increasing residual queue at a node reflects a persistent failure to transmit due to insufficient harvested energy. We therefore set each subframe's WPT duration proportionally to the aggregate queue length of its attributed nodes.

To enable this allocation, each node embeds a quantized queue-length report in its transmitted packet. When node k successfully transmits in frame f , it appends a b -bit quantized representation of its residual queue length $q_k^{(f)}$ to the packet payload. Starting from a uniform initial allocation $t_{\text{wpt},s}^{(1)} = T_{\text{wpt}}/S$, the GW aggregates the reported queue lengths by subframe and updates the WPT duration $t_{\text{wpt},s}^{(f+1)}$ allocated to beam s in frame $f+1$ as

$$t_{\text{wpt},s}^{(f+1)} = T_{\text{wpt}} \cdot \frac{\hat{q}_s^{(f)} + 1}{\sum_{s'=1}^S (\hat{q}_{s'}^{(f)} + 1)}, \quad (7)$$

where

$$\hat{q}_s^{(f)} = \sum_{k: s_k^* = s} \min(q_k^{(f)}, 2^b - 1) \quad (8)$$

is the aggregate capped queue length of nodes attributed to subframe s , where $s_k^* \in \{1, \dots, S\}$ is the index of the WIT window in which node k 's most recent packet was received, and $q_k^{(f)}$ is the residual queue length of node k after transmission in frame f . Nodes that do not transmit in frame f contribute zero to this sum, since the GW receives no fresh report from them; the $+1$ term in (7) prevents any subframe from receiving zero allocation in such cases. Subframes with larger aggregate queue lengths therefore receive longer WPT durations, delivering more energy to the corresponding nodes and reducing their queues.

C. GW-Side Queue Estimation

The GW estimates each node's residual queue length from its reception history alone, requiring no additional uplink overhead. Because each node generates one packet per frame and the buffer is capped at Q_{max} , the number of packets generated but not yet received over a recent window of W frames is a direct indicator of the current queue. Letting $r_k^{(f)}$ denote the cumulative number of packets received from node k by the end of frame f , we estimate

$$\hat{q}_k^{(f)} = \min(Q_{\text{max}}, \max(0, W - (r_k^{(f)} - r_k^{(f-W)}))), \quad (9)$$

where $r_k^{(f-W)} = 0$ for $f \leq W$. The increment $r_k^{(f)} - r_k^{(f-W)}$ counts deliveries in the past W frames, so W minus this difference equals the number of generated packets that the GW has not yet received over the window. We set $W = Q_{\text{max}}$ so that the window matches the maximum number of undelivered packets the buffer can retain. Confining the estimator to a sliding window makes it self-correcting: any overestimation caused by past discards or collision-induced gaps in reception is flushed out of the window after W frames, preventing the permanent positive bias that an unbounded counter would accumulate. Using the subframe attribution s_k^* recorded from each node's most recent reception, the GW forms $\hat{q}_s^{(f)} = \sum_{k: s_k^* = s} \hat{q}_k^{(f)}$ and substitutes the result into (7) in place of explicit queue reports.

TABLE I
Simulation Parameters

Parameter	Symbol	Value
Room size	D	10×10 [m ²]
Number of nodes	N	{5, 10, 15, 20, 25}
ULA elements	M	8
Number of beams	S	8
Carrier frequency	f_c	2.4 [GHz]
Path-loss exponent	α	3.0
Total TX power	P_A	1.0 [W]
Rectification efficiency	ζ	0.5
WPT duration / frame	T_{wpt}	180 [s]
WIT duration / frame	T_{wit}	0.1 [s]
Packet arrival rate	λ	1 [frame/node]
Energy per packet	E_{pkt}	5.76 [μJ]
Overhead energy	E_{ovhd}	2.88 [μJ]
CS energy / attempt	E_{cs}	3.84 [μJ]
Max CS attempts	C_{max}	3
Max aggregation	A_{max}	12
Max queue length	Q_{max}	{5, 7, 10, 15, 20}
Min. node distance	d_{min}	1 [m]
Detection guard	τ_{det}	1 [ms]

IV. SIMULATION RESULTS

Simulations were conducted with $N_f = 1000$ frames per trial and $N_{\text{iter}} = 10000$ independent node placement realizations. Key parameters are listed in Table I. The energy parameters E_{pkt} , E_{ovhd} , and E_{cs} are computed from the current consumption figures specified in the BM70/71 BLE module datasheet [13].

Five adaptive feedback schemes are evaluated alongside two non-adaptive baselines, namely, the Uniform allocation and the BF All-beam, under the proposed per-beam HTT frame structure. *Uniform* performs no queue feedback and allocates equal WPT time to every beam. In *b-bit explicit* feedback ($b = 1, 2, 3$), each node appends b quantized bits of its residual queue length to every transmitted packet; the uplink overhead is very small, e.g., 3 bits added to a 240-bit packet (0.24 [ms] at 1 [Mbps]). The *GW-estimated* approach requires no uplink feedback bits, relying solely on the GW’s reception history via (9). *Exact* reports the true queue length and serves as a reference with perfect queue knowledge at the GW.

A. Scalability with Terminal Count

Fig. 3 plots the delivery ratio versus N for the seven schemes with $Q_{\text{max}} = 7$: the two non-adaptive baselines (Uniform and BF All-beam) and the five feedback-based adaptive schemes. The Uniform allocation remains near 93% regardless of N , as the equal beam allocation provides no mechanism to compensate for heterogeneous node demand. BF All-beam holds near 95% from $N = 5$ to $N = 25$, lying between Uniform and the adaptive schemes; its flat curve confirms that CS effectively suppresses collisions in the single shared WIT window even at $N = 25$.

The five adaptive schemes show different responses to increasing N , reflecting how accurately each scheme can infer node queue lengths under growing WIT-window congestion. *Exact* degrades by about 1.5 pp from $N = 5$ to $N = 25$ as increasing WIT-window congestion limits throughput regardless of WPT allocation accuracy; the $b = 3$ and $b = 2$ schemes

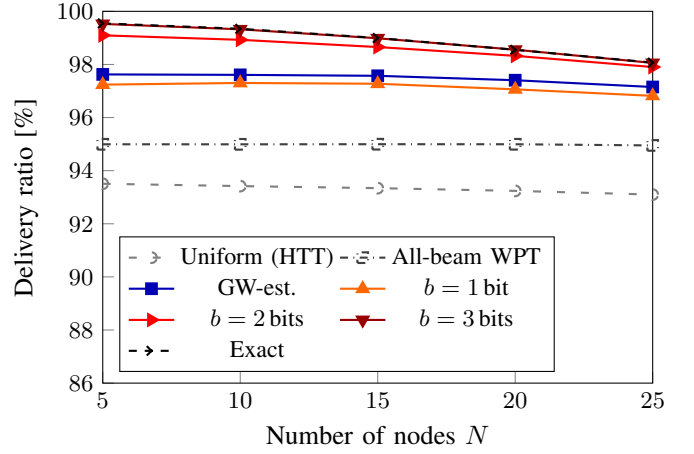


Fig. 3. Delivery ratio versus number of nodes ($M = 8$, $S = 8$, $Q_{\text{max}} = 7$).

track *Exact* closely, since two or more bits suffice to capture the dominant queue structure even under congestion. *GW-estimated*, despite using zero feedback bits, remains slightly above $b = 1$ throughout the range, ending at 97.2% at $N = 25$, a 4.1 pp gain over Uniform’s 93.1%. The sliding-window estimator (9) flushes past discards and collision-induced reception gaps within W frames, so the bias remains bounded even as congestion grows. Because the estimator only resolves the binary distinction between “recent reception” and “no recent reception,” its accuracy ceiling is comparable to that of the $b = 1$ explicit scheme; finer-grained queue information cannot be recovered without per-packet feedback bits.

B. Effect of Buffer Size

Fig. 4 plots delivery ratio versus Q_{max} for all schemes at $N = 10$. The two non-adaptive baselines remain flat across Q_{max} : BF All-beam at about 95.0% and Uniform at about 93.4%. At the default $Q_{\text{max}} = 7$, all queue-aware schemes outperform both baselines: *GW-estimated* reaches 97.6%, $b = 1$ bit 97.3%, $b = 2$ bits 98.9%, $b = 3$ bits and *Exact* both 99.3%. Their sensitivity to Q_{max} differs markedly. *GW-estimated* rises monotonically from 97.3% at $Q_{\text{max}} = 5$ to 98.7% at $Q_{\text{max}} = 20$ (+1.4 pp): a wider buffer allows the sliding window $W = Q_{\text{max}}$ in (9) to integrate over more frames, suppressing the variance of the reception-gap estimate. The $b = 1$ bit scheme is virtually flat (97.3–97.4%) because a single bit cannot distinguish nodes with one queued packet from those holding Q_{max} packets, so the effective allocation does not change with buffer depth. The $b = 2$ bit scheme gains only 0.2 pp from $Q_{\text{max}} = 5$ to 20, indicating that two bits already capture the queue variation that drives WPT reallocation at this operating point. By contrast, $b = 3$ and *Exact* continue to benefit from larger buffers, gaining 0.7 pp and 0.8 pp, respectively: a finer queue resolution lets the GW progressively shift WPT time toward nodes with deep backlogs.

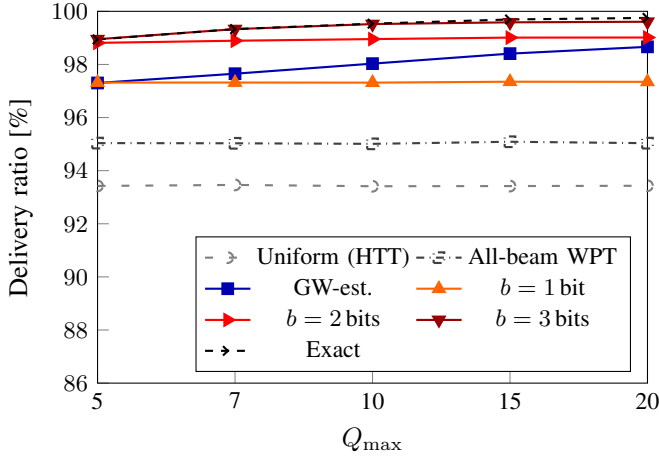


Fig. 4. Delivery ratio versus buffer size $Q_{\max}$ ($M = 8$, $S = 8$, $N = 10$).

C. Terminal Fairness Analysis

Fig. 5 shows the CDF of the per-node delivery ratio across all the node placements and iterations.

The GW-estimation scheme's per-node estimate (9) rises whenever a node's recent reception count falls short of the window length W , providing an autonomous queue signal that the Uniform baseline lacks; this progressive adaptation to persistent reception shortfalls reduces the per-node delivery ratio dispersion compared to the non-adaptive baselines. Among the explicit-feedback schemes, $b = 3$ bits produces a distribution virtually identical to Exact since $\min(q, 7) = q$ for $q \leq Q_{\max} = 7$, so three bits fully represent the queue depth at this buffer size.

Fig. 5 reveals that the performance gap between Uniform and the proposed schemes is driven largely by fairness: both Uniform and BF All-beam leave a substantial fraction of nodes below an 80% individual delivery ratio, since the fixed allocation cannot adapt to heterogeneous channel conditions. The GW-estimated and $b = 2$ bit schemes raise the lower 5th percentile above 94%, and the $b = 3$ bit curve is virtually indistinguishable from Exact, whereas $b = 1$ bit provides an intermediate improvement with a lower 5th percentile of 76%.

V. CONCLUSION

This paper proposed a per-beam harvest-then-transmit (HTT) protocol with a queue-length-proportional WPT time allocation for indoor beamforming SWIPT systems. By allocating WPT time in proportion to the aggregate queue lengths, the proposed protocol redirects energy toward backlogged beams and improves the packet delivery ratio by up to 4.3 pp over equal-time beamforming at $N = 10$ and $Q_{\max} = 7$. Notably, the zero-overhead GW-side estimator attains 97.6% without any uplink feedback, and two-bit explicit feedback comes within 0.4 pp of the full-feedback upper bound. In practice, GW-side estimation is preferred when uplink overhead is a concern and traffic is regular enough for the reception-gap counter to track the queue, whereas explicit feedback is preferred when finer queue resolution is needed, such as

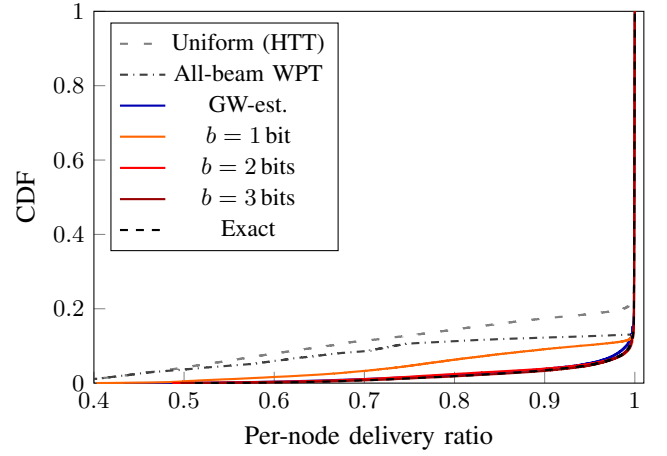


Fig. 5. CDF of per-node delivery ratio ($M = 8$, $S = 8$, $N = 10$, $N_{\text{iter}} = 10000$).

for deep buffers or bursty backlogs, where $b \geq 2$ materially improves allocation at the cost of a few bits per packet. Future work includes modeling storage self-discharge over the long WPT frames and evaluating the protocol under bursty or Poisson traffic.

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