Multi-gateway Polling for Nanonetworks under Dynamic IoT Backhaul Bandwidth

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***Abstract*—As an emerging part of the Internet of Things (IoT), Electromagnetic-based Wireless NanoSensor Networks (EM-WNSNs) working in the TeraHertz (THz) band are envisaged to enable applications that demand high sensing resolution. For high-speed nanonetworks deployed for time-critical applications, the limited IoT backhaul bandwidth of the existing infrastructure becomes the bottleneck that deteriorates resource utilization efficiency. On the one hand, the bandwidth demand exceeding the supply results in unnecessary energy consumption on nano-devices as overdue data are discarded. On the other hand, the excess supply of bandwidth reduces the bandwidth efficiency. To address this problem, the On-demand Efficient (OE) polling and On-demand Probabilistic (OP) polling were proposed for single-gateway scenarios whereas deploying multiple gateways can achieve higher data completeness and energy efficiency. Therefore, in this paper, we propose the Multi-gateway Probabilistic (MP) polling scheme for multi-gateway EM-WNSNs. To achieve high bandwidth efficiency, in MP polling, one master gateway is selected for OP polling with the aggregated bandwidth that reduces the probabilistic uncertainty. Next, all gateways probabilistically receive packets using the bandwidth-based receiving windows. To the best of our knowledge, MP Polling is the first polling solution designed for multi-gateway EM-WNSNs under dynamic backhaul bandwidth.**

I. INTRODUCTION

Driven by the rapid development of graphene-based technologies, research on Electromagnetic-based Wireless NanoSensor Networks (EM-WNSNs) [1] has rapidly progressed recently. Characterized by the high-speed TeraHertz (THz) pulse and nano-scale network devices, EM-WNSNs provide non-invasive precise sensing to enable a wide range of novel applications that require high sensing resolution. To take the advantage of those motivating features, EM-WNSNs are expected to be connected to the Internet of Things (IoT) as the Internet of Nano Things (IoNT).

In the network architecture depicted in Fig. 1, IoNT is composed nanosensors and nano-sinks that form the data tier for event sensing and backhaul tier for data aggregation, respectively. Next, nanonetworks are bridged to the Internet via IoT gateways and backhaul stations (e.g. eNodeB) of the micro-scale infrastructure. Unfortunately, backhaul stations with existing IoT backhaul technologies [2] allocate limited and dynamic bandwidth to Machine-Type Communication (MTC) [3] and thus bring a new challenge for the high-speed nanonetworks deployed for time-critical applications [4]. On the one hand, the EM-WNSNs throughput exceeding the

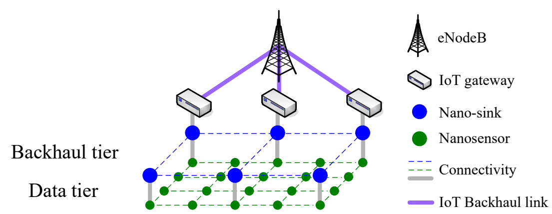


Fig. 1: EM-WNSNs bridged to the IoT gateway

bandwidth supply results in unnecessary energy consumption on nano-devices due to the overdue data discarded by traffic policing. On the other hand, the excess supply of bandwidth reduces the bandwidth utilization efficiency. To optimize both the energy efficiency of nanonetworks and bandwidth efficiency of backhaul networks, the EM-WNSNs throughput must match the allocated backhaul bandwidth.

Existing solutions addressing this problem focus on the single-gateway scenario [5]–[7] whereas deploying multiple gateways becomes necessary when the completeness of time-critical data collection and energy efficiency of nano-devices are expected to be improved. Therefore, we propose Multi-gateway Probabilistic (MP) polling. To achieve high bandwidth efficiency, MP polling selects the master gateway that aggregates the bandwidth of all gateways for probabilistic polling [6]. In this way, the uncertainty introduced by the probabilistic process is reduced so as to improve the bandwidth efficiency. Next, to determine the addresses of destination gateways for nano-sinks, message packets are configured with random destinations and gateways probabilistically collect data via the bandwidth-based receiving windows.

The rest of the paper is organized as follows. The related work on data acquisition in EM-WNSNs are reviewed in Section II, followed by the system model in Section III. The design of MP polling is presented in Section IV. Then, performance of MP Polling is evaluated and discussed in Section V followed by the conclusions in Section VI.

II. RELATED WORK

The first work that bridges EM-WNSNs to the overall IoT is the On-demand Efficient (OE) polling [5]. By evenly adjusting the data volume of each nano-sink in the polling process, OE polling aims to match the EM-WNSNs throughput and the given backhaul bandwidth under dynamic nano-scale and micro-scale network conditions. However, OE polling fails to utilize the residual bandwidth that results from the per-sink bandwidth allocation.

To improve the bandwidth efficiency of OE polling, the On-demand Probabilistic (OP) polling [6] was proposed as the enhancement. Compared with OE polling, OP polling adopts an additional probabilistic process that fairly selects nano-sinks for sharing the residual bandwidth. Specifically, the number of packets to poll from each sink, n, is given by:

$$n = \frac{P_{opt}}{N_{max}} = n_I + n_R, \tag{1}$$

where P_{opt} is the optimal number of packets to poll for the given bandwidth, N_{max} is the number of sinks reachable by the gateway, n_I is the integral part of the division denoting the deterministic number of packets to poll while the decimal n_R is the threshold to trigger the probabilistic process for utilizing the residual bandwidth.

Benefiting from this operation, the bandwidth efficiency of OP polling is improved. Nonetheless, deploying the single-gateway OP polling on individual gateways deteriorates the overall bandwidth efficiency because the low bandwidth with small P_{opt} at each gateway leads a high proportion of n_R with probabilistic uncertainty. Therefore, MP polling, which is enhanced based on OP polling, is proposed to improve the bandwidth efficiency.

III. System Model

A. Communication Model

For simplicity, nano-devices and IoT gateways are equipped with omni-directional antennas. Additionally, IoT gateways are assumed to support both the THz and lower-frequency links to communicate with nano-devices and backhaul stations, respectively. Due to the small antenna size and energy capacity, communications among nano-devices and IoT gateways are carried by the THz pulses modulated using the Time Spread On-Off Keying (TS-OOK) [8]. The packet receiving process is determined by the RSSI threshold. In this work, the channel condition is assumed to be static by adopting a constant humidity level.

B. Network Model

The hierarchical network architecture in Fig. 1 is assumed with the topology comprising N_{max} nano-sinks and N_{GW} gateways that are statically and randomly deployed following the uniform distribution. Besides, nano-sinks and gateways are equipped with homogeneous THz transceivers with the maximal transmission power so as to achieve full network connectivity and minimal latency. Considering the low capacity of nano-devices, the dissemination of beacons and data packets is implemented by the Selective Flooding scheme proposed for nanonetworks [9].

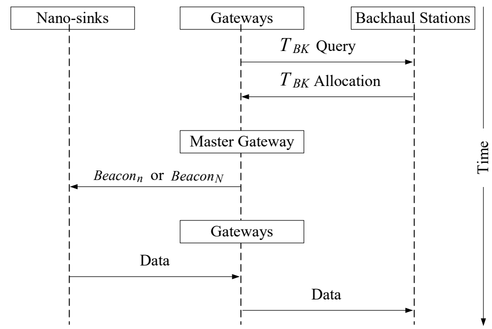


Fig. 2: Message sequence of MP polling

Algorithm 1 MP polling for IoT gateways

Initialization

Gateways query T_{BK}^i, calculate P_{opt}^i in Eqn. (2), P_{opt}^{total} in Eqn. (3), RB_i in Eqn. (4), Set $P_c^i = 0, n_R = 0, n_I = 0$.

Probabilistic polling

For the master gateway:

```
if P_opt^total > 0 then
    n_I = ⌊P_opt^total / N_max⌋, n_R = 100 (P_opt^total mod N_max) / N_max
    if n_R == 0 or n_I == n_max then
        Send Beacon_n with Field_n = n_I // see Fig. 3
    else
        Send Beacon_N with Field_n = n_I, Field_N = n_R
    end if
end if
```

Probabilistic receiving

When the i-th gateway receives a message packet:

```
if RB_{i-1} < Rdst ≤ RB_i and P_c^i < P_opt^i then
    Keep the packet
    P_c^i ++
else
    Drop the packet
end if
```

IV. Multi-gateway Probabilistic Polling

The message exchange sequence and operations for gateways are presented in Fig. 2 and Algorithm 1, respectively. The operations of MP polling consist of three steps: 1) the master gateway executes probabilistic polling for all gateways using the total bandwidth, 2) nano-sinks send message packets with random destinations, and 3) gateways receive packets using probabilistic receiving windows.

As shown in Algorithm 1, given the delay constraint of the i-th gateway denoted by D^i and the packet size p, the MP polling cycle starts with an initialization and coordination process wherein the i-th gateway firstly queries its bandwidth $T_{BK}^i = \alpha^i T_{BK}^{max}$ where $\alpha^i \sim U(0,1)$ is the dynamic ratio of the bandwidth allocated to the i-th gateway from its total bandwidth T_{BK}^{max}. Next, the i-th gateway calculates the optimal number of packets P_{opt}^i in Eqn. (2) [6] with $P_{opt}^0 = 0$, the total optimal number of packets P_{opt}^{total} in Eqn. (3), and the upper bound of its probabilistic receiving window RB_i in Eqn. (4). Besides, the packet counter P_c^i is set to 0.

$$P_{opt}^i = \lfloor \frac{T_{BK}^i D^i}{p} \rfloor, \; i \in \mathbb{Z}_{\geq 0} : i \in [0, N_{GW}]. \tag{2}$$

$$P_{opt}^{total} = \sum_{1}^{N_{GW}} P_{opt}^i, \; i \in \mathbb{Z}_{\geq 0} : i \in [1, N_{GW}]. \tag{3}$$

$$RB_i = \frac{100 \sum_{0}^{i} P_{opt}^i}{P_{opt}^{total}}, \; i \in \mathbb{Z}_{\geq 0} : i \in [0, N_{GW}]. \tag{4}$$

Next, the master gateway conducts the probabilistic polling [6] in Algorithm 1. First, as shown in line 2, n_I and n_R in Eqn. (1) are calculated using P_{opt}^{total}. Two types of beacons, viz. $Beacon_n$ and $Beacon_N$ as shown in Fig. 3, are adopted to carry the values of n_I and n_R. Specifically, $Beacon_n$ is used when $n_R = 0$ indicating the full utilization of bandwidth, or sinks need to respond with the maximal number of packets $n_I = n_{max}$. In this case, following lines 3 - 4, the calculated n_I is inserted into $Field_n$ of $Beacon_n$. Otherwise, $Beacon_N$ is adopted to notify nano-sinks with n_I and n_R that are inserted into $Field_n$ and $Field_N$ of $Beacon_N$, respectively. Then, the beacon is broadcasted to all nano-sinks.

Upon receiving a $Beacon_n$, a sink responds to polling with $Field_n$ packets. If a $Beacon_N$ is received, a sink generates an uniform random integer $r \in \mathbb{Z}_{\geq 0} : r \sim U(0, 100)$ and compares r with $Field_N$. Next, $Field_n + 1$ packets are aggregated if $r < Field_N$. Otherwise, $Field_n$ packets are aggregated. In this way, the expectation of the total number of packets polled becomes P_{opt}^{total}.

In MP polling, receiving the polled message packets is challenging because the polling beacon sent by the master gateway contains no explicit destination information that directs P_{opt}^i unique packets to the i-th gateway. To eliminate additional coordination among nano-sinks, probabilistic receiving is developed as a solution. Specifically, every packet is configured with a random destinations $R_{dst} \in \mathbb{Z}_+ : R_{dst} \sim U(1, 100)$ and the i-th gateway receives packets using its probabilistic receiving windows $RW_i = (RB_{i-1}, RB_i]$ for which the interval indicates the ratio of P_{opt}^i to P_{opt}^{total}, as presented in Fig. 4. For the i-th gateway, a message packet is retained when its random destination falls in the receiving window and the number of packets collected is fewer than P_{opt}^i, as presented by lines 1 - 3 in the probabilistic receiving of Algorithm 1. Otherwise, this packet is discarded. In this way, P_{opt}^i unique packets are expected to be received by the i-th gateway.

V. Performance Evaluation

In this section, we first model the performance metrics and propose one benchmark polling scheme. Then, the simulation parameters are listed. At last, the results of performance evaluation are analysed.

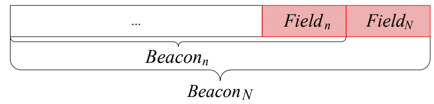


Fig. 3: Beacon structure

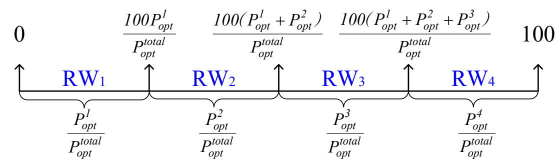


Fig. 4: Probabilistic receiving window for gateways

A. Performance metrics

The proposed OE polling is evaluated using the following performance metrics:

1) Bandwidth efficiency, BE:

$$BE = \frac{\sum_{1}^{N_{GW}} \frac{P_{EM-WNSNs}^i}{P_{opt}^i}}{N_{GW}}, \tag{5}$$

where $P_{EM-WNSNs}^i$ is the number of packets collected by the i-th gateway.

2) Energy consumption for polling one packet, E:

$$E = \frac{E_{total}}{\sum_{1}^{N_{GW}} P_{EM-WNSNs}^i} \tag{6}$$

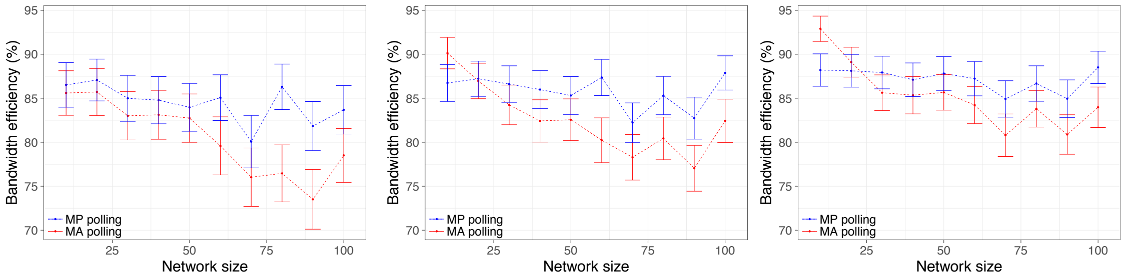
where E_{total} is the total energy consumption of packet processing during one polling process.

B. Benchmark

The Multi-gateway Autonomous (MA) polling is selected as comparison. In MA polling, gateways conduct OP polling autonomously without coordination. In response, sinks transmit message packets to individual gateways using explicit destination addresses.

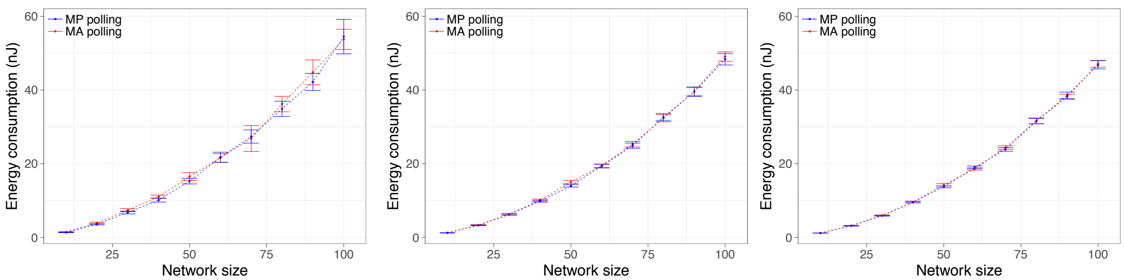
C. Simulation parameters

The performance of MP polling and MA polling are evaluated using the Nano-Sim [9]. Each bit of data is carried by one 100-fs-long pulse on 1 THz with 1 pJ energy. The receiving sensitivity of nano devices is set to -130 dBm considering the high sensitivity of nano materials [1]. Each unit message packet generated by a nano sensor contains 100 bits. The maximal packet aggregation size is set to 10 packets. The backhaul link with total bandwidth capacity T_{BK}^{max} of 500 Kbps, 1000 Kbps, and 1500 Kbps are adopted to serve the polling process with delay tolerance D of 1 ms. For each polling, $\alpha_i \sim U(0, 1)$ is generated to implement the dynamic IoT backhaul capacity. From 10 to 100 static nano sinks are uniformly randomly deployed in a 10m-by-10m area whereby four IoT gateways are located at (0m,0m), (0m,7.5m), (7.5m,0m), and (7.5m,7.5m) among which the first one is



(a) $T_{BK}^{max} = 500Kbps$ (b) $T_{BK}^{max} = 1000Kbps$ (c) $T_{BK}^{max} = 1500Kbps$

Fig. 5: Bandwidth efficiency



(a) $T_{BK}^{max} = 500Kbps$ (b) $T_{BK}^{max} = 1000Kbps$ (c) $T_{BK}^{max} = 1500Kbps$

Fig. 6: Energy consumption

selected as the master. All nodes are fully connected via multiple hops. Each result presented is the mean and 95% confidence interval with normally distributed error obtained from 100 simulations.

D. *Results and analysis*

The results for bandwidth efficiency and energy consumption for different bandwidth levels are presented in Fig. 5 and 6. From Fig. 5, the proposed MP polling achieves a bandwidth efficiency that is maximally 9.84% higher than MA polling, which benefits from the aggregated P_{opt}^{total} that reduces the proportion of n_R in Eqn. (1) that causes probabilistic uncertainty. Overall, for each T_{BK}^{max}, bandwidth efficiency decreases when network size increases due to the increased proportion of n_R in Eqn. (1). On the contrary, the increase of T_{BK}^{max} improves bandwidth efficiency as it reduces the proportion of packets probabilistically polled.

As shown in Fig. 6, MP polling shows slightly lower energy consumption that is 98.54% of that of MA polling. On the one hand, for a given T_{BK}^{max}, energy consumption for polling each packet is positively related to network size that impacts the energy cost of flooding. On the other hand, energy consumption decreases for an increased T_{BK}^{max} that improves the bandwidth efficiency.

VI. Conclusions

In this paper, MP polling is proposed based on the previous implemented OP polling to support multi-gateway scenarios. With multiple gateways' bandwidth aggregated, MP polling aims to achieve high bandwidth efficiency by reducing the uncertainty of probabilistic polling. Overall, MP polling outperforms MA polling in bandwidth efficiency while achieving as good, if not better, energy consumption.

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