Elimination of Multi-hop Transmission from Downlink in Low Power and Lossy Networks

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Abstract—In this paper, we consider the use of an electric-supplied coordinator exploiting much higher transmission power than battery-supplied nodes in low power and lossy networks (LLNs). Since the coordinator can transmit via one hop instead of multiple hops over downlink, it is possible to reduce the communication overhead significantly. To take this advantage, we propose a single hop downlink protocol (SHDP) which comprises direct downlink transmission, local acknowledgement, neighbor forwarding, and mitigation of forwarding contention. Finally, the performance of the proposed SHDP is mathematically analyzed and evaluated by computer simulation, showing significant performance improvement over conventional multi-hop routing when applied to LLNs.

Keywords—low power and lossy network, heterogeneous power network, automatic price tag update, downlink protocol

I. INTRODUCTION

Multi-hop communication has been considered as a necessary feature in a low power and lossy network (LLN) since battery power supply significantly limits the transmission power of nodes [1]. Since traditional LLN applications (e.g., environment monitoring) mainly generate uplink traffic, LLN researchers have focused on the design of uplink routing technique. However, some valuable downlink-centric applications need an efficient downlink transmission protocol. For example, automatic price tag update service, which has sufficient marketability, makes the coordinator transmit price information to an LED price tag of each product.

Unlike uplink routing [2], [3], downlink routing has a great number of destinations, generating large control messages and memory overhead to manage routing tables. For example, RPL, a recent routing standard for LLNs, makes each node transmit a control message (i.e., DAO) to the coordinator in a multi-hop manner to provide the path information between the coordinator and node [3]. In fact, secure delivery of the multi-hop control message to the sink is an overhead and challenging task [4]. RPL reconstructs the whole downlink routing topology whenever any link is disconnected, thus yielding significantly large overhead of the control message [5]. Also, multi-hop communication causes unfair energy consumption among nodes, since nodes near the coordinator suffer from much more burden for relaying packets than those far from the coordinator [6]. Thus, it may be desirable to design a lightweight downlink transmission scheme to support downlink-centric applications.

In this paper, we consider an electric-supplied coordinator which uses much higher transmission power than battery-supplied nodes. It is noted that use of permanent power supply for the coordinator is a common assumption in most research for LLNs [7]. In particular, we propose a single hop downlink protocol (SHDP) where the coordinator directly transmits a downlink packet to the destination node. The proposed SHDP is free from multi-hop acknowledgement transmission due to the use of local acknowledgement, neighbor forwarding, and mitigation of forwarding contention. The performance of the proposed SHDP is mathematically analyzed and evaluated by computer simulation, which shows significant performance improvement over conventional schemes.

The rest of this paper is organized as follows. Section II illustrates the system model in consideration. Section III describes the proposed SHDP and Section IV analyzes its performance. Section V evaluates the performance of the SHDP by computer simulation. Finally, Section VI concludes this paper.

II. SYSTEM MODEL

A. Network model

Consider an LLN where $N_{\text{tot}}$ nodes, uniformly distributed throughout the network area, receive downlink data from the coordinator. Suppose each node has transmission range $r$ and $N_{\text{ne}}$ neighbor nodes within a circular area of radius $r$. A certain node is supposed to be able to receive a packet transmitted from another node within $r$ with packet error rate $e$. In this paper, we consider the multi-hop downlink protocol (MHDP), an ideal multi-hop protocol, as a conventional scheme that allows the coordinator to freely know a downlink routing path that minimizes the hop distance to each node. Without control overhead of routing path discovery, MHDP achieves the best performance among all conventional multi-hop protocols. Thus, SHDP may guarantee performance improvement over any real multi-hop protocol when it outperforms MHDP. We assume that SHDP makes the coordinator exploit high power enough to cover the whole network area. As the baseline medium access control (MAC) protocol for MHDP and SHDP, we consider BoX-MAC-2 [8], the standard MAC layer of TinyOS that is widely used in LLNs [7].
B. BoX-MAC-2

We here briefly describe the operation of BoX-MAC-2 [8]. Each node periodically wakes up and checks during the channel sensing period whether the channel is busy or not. The node falls asleep again when the channel is idle. When detecting that the channel has an ongoing packet, it starts to receive the packet. If the destination address of the packet is the same as that of the node, the node transmits an acknowledgement to the sender after finishing reception; otherwise, the node falls asleep again. BoX-MAC-2 allows each node to overhear a packet transmitted from a sender within the transmission range irrespective of the destination. A node willing to send a packet first performs channel sensing after random backoff. Then, it repetitively transmits the packet during the wake-up interval if the channel is free, while extending the backoff number and, if busy, retries to send the packet. Each packet is thus delivered via repetitive transmissions during the wake-up interval. The sender finishes the repetitive transmission when receiving an acknowledgement. The sender can retransmit the packet $N_s$ times maximally, when it fails to receive the acknowledgement. The channel sensing period needs to be longer than or equal to the inter packet interval (i.e., backoff period) to reliably detect whether the channel has an ongoing packet transmission or not.

III. PROPOSED SHDP

The proposed SHDP comprises high-power transmission of the coordinator and low-power transmission of nodes\(^1\). Note that a destination node may fail to directly transmit an acknowledgement to the coordinator due to the long distance. To provide reliable data delivery without multi-hop acknowledgement transmission, node reactions consist of local acknowledgement, neighbor forwarding, and mitigation of forwarding contention.

The detailed operation of the SHDP is depicted in fig. 1 and described below. In this example, the coordinator (i.e., node 0) transmits a packet to node 1 which has node 2 and node 3 as its neighbors. Fig. 1-(b) and fig. 1-(c) depict successful direct transmission and neighbor forwarding after direct transmission failure, respectively.

A. Coordinator operation

The coordinator (i.e., node 0) directly transmits a packet to the destination node with use of high power. It does not expect to receive the acknowledgement, and thus, repetitively transmits the packet throughout the whole wake-up interval. To support acknowledgement reception of the neighbor nodes, the coordinator inserts a sequence number to the packet. The sequence number is initially set as the total number of repetitive transmissions during the wake-up interval and decremented by one per retransmission (i.e., the last packet contains the sequence number of zero).

\(^{1}\text{Maximum transmission power of CC2420 (i.e., representative commercial low power transceiver) is 0dBm, while that of the coordinator is 30dBm according to FCC power regulation for ISM band.}\)

![Fig. 1. An example of SHDP operation.](image)

B. Node operation

When a node wakes up and receives a packet, it first checks the destination address of the packet. If the node is the destination (e.g., node 1 in fig. 1-(b)), it checks whether the sequence number of the packet is zero. If the sequence number is zero, the node broadcasts an acknowledgement to its neighbor nodes (e.g., node 2 and node 3 in fig. 1-(b)). If the sequence number is $s > 0$, the node falls asleep again during $t_{\text{sleep}}$ for saving energy. The interval from finishing the transmission of a packet with sequence number $s$ to starting the transmission of a packet with sequence number $0$, $t_s$, can be represented as

$$t_s = (s - 1)t_{\text{packet}} + \sum_{i=0}^{s-1} t_{b_{0,i}} \quad (1)$$

where $t_{\text{packet}}$ is the packet length and $t_{b_{0,i}}$ is the backoff time (randomly chosen between 0 and maximum $t_{b_{0,\text{max}}}$) before transmitting packet $i$. To guarantee that the node receives a packet of sequence number zero (i.e., $t_{\text{sleep}} \leq t_s$), $t_{\text{sleep}}$ can be determined as

$$t_{\text{sleep}} = (s - 1)t_{\text{packet}}. \quad (2)$$

Thus, the main differences from the baseline MAC are that a destination is required to receive packet 0 for acknowledgement transmission and that neighbors of the destination
receive acknowledgement instead of the sender. If the received packet contains no sequence number, the node transmits an acknowledgement since the packet is sent from a neighbor node (e.g., node 1 in fig. 1-(c)).

If the node is not the destination, it checks whether the destination is one of its neighbors or not. If the node is not a neighbor of the destination, it falls asleep again during the wake-up interval (e.g., node 4 in fig. 1-(b)). If the destination is its neighbor node, the node first operates in the same way as the destination node to receive packet 0. After receiving the packet 0, the node listens to the channel to receive an acknowledgement from the destination node. The node falls asleep again after receiving an acknowledgement (e.g., node 2 in fig. 1-(b)). Otherwise, it starts to forward the packet (e.g., node 2 and node 3 in fig. 1-(c)).

Forwarding process is the same as the packet transmission of the baseline protocol. Thus, a forwarded packet does not contain the sequence number. Also, a forwarding node can retransmit the packet since it can confirm the packet delivery by receiving an acknowledgement. When a forwarding node overhears any packets before transmitting a forwarded packet, it checks the destination address of the overhead packet. If the destinations of the overhead packet and the forwarded packet are same, the forwarding node discards the forwarded packet (e.g., node 3 in fig. 1-(c)). Thus, SHDP allows only the forwarding node which occupies the channel first to continue the forwarding process (e.g., node 2 in fig. 1-(c)), thus mitigating contention among multiple forwarding nodes.

IV. PERFORMANCE ANALYSIS

We mathematically analyze the energy consumption of the MHDG and SHDP. Let \( d_{hop}(k) \) be the hop distance between the coordinator and node \( k \) when the coordinator exploits low power, and it is represented as

\[
d_{hop}(k) = \left\lfloor \frac{d(k)}{r} \right\rfloor \tag{3}
\]

where \( d(k) \) and \( \lfloor x \rfloor \) denote a physical distance between the coordinator and node \( k \) and the smallest integer larger than or equal to \( x \), respectively. Assuming that the wake-up interval is long enough to make the destination and its neighboring nodes need to receive two repetitive transmissions of a packet (i.e., packet \( s > 0 \) and \( t \)) to transmit and receive an acknowledgement. For mathematical tractability, we assume that a node transmits a packet without contention, collision, and queuing delay (i.e., consider only channel error). Our assumption is valid in an automatic price tag update scenario where only the coordinator generates low rate downlink traffic. In general, the analysis can show the upper bound performance.

A. Basic analysis

Let \( t_{packet} \) and \( t_{ack} \) be the time length of a data packet and acknowledgement, respectively. Assume that \( p_{rx}, p_{tx}, p_{cs}, \) and \( p_{dl} \) are power consumption for transmission, reception, channel sensing, and backoff, respectively. Then, each node periodically wakes up and consumes energy \( \varepsilon_{cs} \) for channel sensing to check whether the medium is idle or not, which is represented by

\[
\varepsilon_{cs} = p_{cs} \left( t_{ack} + t_{bo, max} \right). \tag{4}
\]

Letting \( T \) denote the time observed to measure the consumed energy, total energy consumption for a medium check, \( \varepsilon_{cs,tot} \), can be expressed by

\[
\varepsilon_{cs,tot} = \frac{N_{tot} T \varepsilon_{cs}}{t_{wakeu}}. \tag{5}
\]

Note that \( \varepsilon_{cs,tot} \) is the basic energy consumption without any packet transmission or reception and \( \varepsilon_{cs,tot} \) decreases as \( t_{wakeu} \) increases.

A node that is willing to send a packet first performs channel sensing and consumes \( \varepsilon_{cs} \). When the channel is idle, the sender transmits a packet repetitively. A successful packet transmission may last for \( \frac{t_{wakeu}}{2} \), while a failed one for \( t_{wakeu} \). Thus, the number of repetitive packets for a successful transmission and failed transmission, \( n_{ts,s} \) and \( n_{ts,f} \), is represented as, respectively,

\[
n_{ts,s} = \left[ \frac{t_{wakeu}}{2 \left( t_{packet} + t_{ack} + t_{bo, max}/2 \right)} \right], \tag{6}
\]

\[
n_{ts,f} = \left[ \frac{t_{wakeu}}{t_{packet} + t_{ack} + t_{bo, max}/2} \right]. \tag{7}
\]

Then, the energy consumption for a successful and failed packet transmission, \( \varepsilon_{ts,s} \) and \( \varepsilon_{ts,f} \), respectively, is expressed by

\[
\varepsilon_{ts,s} = \varepsilon_{cs} + n_{ts,s} \varepsilon_{tx}, \tag{8}
\]

\[
\varepsilon_{ts,f} = \varepsilon_{cs} + n_{ts,f} \varepsilon_{tx}. \tag{9}
\]

Here \( \varepsilon_{tx} \) is the energy consumption for a repetitive transmission, which is calculated as

\[
\varepsilon_{tx} = \frac{p_{dl} t_{bo, max}}{2} + p_{tx} t_{packet} + p_{rx} t_{ack}, \tag{10}
\]

since it comprises random backoff, packet transmission, and acknowledgement reception. Here, \( \varepsilon_{ts,s} \) and \( \varepsilon_{ts,f} \) increase as \( t_{wakeu} \) increases. Assuming that the collision effect is negligible, the total energy consumption for a sender and receiver until a one-hop transmission ends, \( \varepsilon_{rx,one} \) and \( \varepsilon_{tx,one} \), respectively, is calculated as

\[
\varepsilon_{tx,one} = \left( 1 - e \right) \sum_{i=0}^{N_{ts}} \varepsilon_{tx,one} + \varepsilon_{tx} e^i \tag{11}
\]

\[
\varepsilon_{rx,one} = p_{rx} t_{packet} \left( 1 - e \right) \sum_{i=0}^{N_{ts}} \varepsilon_{rx,one} + p_{tx} t_{ack} \left( 1 - e \right) \tag{12}
\]

\[
= \left( 1 - e \right) \left( p_{tx} t_{ack} + \frac{p_{rx} t_{packet}}{1 - e} \right). \tag{13}
\]
It is seen that $\varepsilon_{tx,one}$ increases as $t_{wakeup}$ increases due to the characteristics of $\varepsilon_{tx,s}$ and $\varepsilon_{tx,f}$.

When a sender transmits a packet to the destination, neighbor nodes of the destination overhear the packet. When the packet transmission is successful, only half of the neighbor nodes may overhear the packet since the repetitive transmission stops after $t_{wakeup}/2$. Otherwise, the whole neighbor nodes may overhear the packet. Thus, the energy required for overhearing a successful or failed packet transmission, $\varepsilon_{oh,s}$ or $\varepsilon_{oh,f}$, can be represented as, respectively,

$$\varepsilon_{oh,s} = \frac{prx_{t}packetN_{ne}}{2},$$

$$\varepsilon_{oh,f} = prx_{t}packetN_{ne}.\quad(13)$$

Then, the total energy consumption for overhearing until a one-hop transmission ends, $\varepsilon_{oh,one}$, can be expressed by

$$\varepsilon_{oh,one} = (1 - e) \sum_{i=0}^{N_{tx}-1} (\varepsilon_{oh,s} + i\varepsilon_{oh,f}) e^i + N_{tx}\varepsilon_{oh,f} e^{N_{tx}}$$

$$= (1 - e^{N_{tx}}) \left( \varepsilon_{oh,s} + \varepsilon_{oh,f} \frac{e}{1 - e} \right).$$

### B. Analysis of MHDP

When a coordinator delivers a packet to node $k$ in case of MHDP, $N_{hop}(k)$ senders and $N_{hop}(k)$ receivers are required to participate in the packet delivery. Then, the total energy consumption for $N_{hop}(k)$ senders and $N_{hop}(k)$ receivers, $E_{MHDP}^{tx}(k)$ and $E_{MHDP}^{rx}(k)$, respectively, is calculated as

$$E_{MHDP}^{tx}(k) = \varepsilon_{tx,one} \sum_{i=0}^{N_{hop}(k)-1} \left( 1 - e^{N_{tx}} \right) e^i$$

$$= \varepsilon_{tx,one} \left( 1 - e^{N_{tx}} \right) \left( 1 - \left( 1 - e^{N_{tx}} \right)^{N_{hop}(k)-1} \right) e^{N_{tx}}.$$ \quad(16)

$$E_{MHDP}^{rx}(k) = \varepsilon_{rx,one} \sum_{i=0}^{N_{hop}(k)-1} \left( 1 - e^{N_{tx}} \right) e^i$$

$$= \varepsilon_{rx,one} \left( 1 - \left( 1 - e^{N_{tx}} \right)^{N_{hop}(k)} \right) e^{N_{tx}}. \quad(17)$$

Here the energy consumption of a coordinator is ignored, since the coordinator is supposed to have permanent power supply. In each transmission, neighbor nodes overhear the packet at the cost of more consumed energy. Then, energy consumption for overhearing when a coordinator delivers a packet to node $k$, $E_{MHDP}^{oh}(k)$, can be expressed by

$$E_{MHDP}^{oh}(k) = \varepsilon_{oh,one} \sum_{i=0}^{N_{hop}(k)-1} \left( 1 - e^{N_{tx}} \right) e^i$$

$$= \varepsilon_{oh,one} \left( 1 - \left( 1 - e^{N_{tx}} \right)^{N_{hop}(k)} \right) e^{N_{tx}}. \quad(18)$$

It is seen that $E_{MHDP}^{tx}(k)$, $E_{MHDP}^{rx}(k)$, and $E_{MHDP}^{oh}(k)$ increase as $N_{hop}(k)$ increases since the number of relay nodes increases. It is also seen that nodes near a coordinator may consume much more energy than those far from the coordinator due to the heavy burden for relaying. It is shown from (11) and (16) that $E_{MHDP}^{tx}(k)$ increases as $t_{wakeup}$ increases.

The inter packet interval is denoted by $t_{in}$, and a coordinator is assumed to equally generate a packet for each node. Then, the number of packets generated for each node during $T$, $N_{packet}$, is written as

$$N_{packet} = \frac{T}{t_{in}N_{tot}}. \quad(19)$$

The total energy consumption by all the nodes with the use of MHDP during the experiment time $T$, $E_{MHDP}$, is calculated as

$$E_{MHDP} = \varepsilon_{cs,tot} + N_{packet} \sum_{k=1}^{N_{tx}} \left( E_{MHDP}^{tx}(k) + E_{MHDP}^{rx}(k) + E_{MHDP}^{oh}(k) \right). \quad(20)$$

$E_{MHDP}$ has a trade-off in terms of $t_{wakeup}$, because $E_{MHDP}^{tx}(k)$ increases and $\varepsilon_{cs,tot}$ decreases as $t_{wakeup}$ increases. In particular, $E_{MHDP}^{tx}(k)$ sharply increases with $t_{wakeup}$ when $N_{packet}$ and/or the network size are large. Thus, MHDP cannot efficiently support the use of low duty cycle in large scale LLNs, thereby significantly restricting the energy efficiency.

### C. Analysis of SHDP

When the coordinator delivers a packet in case of SHDP, only two senders (i.e., the coordinator and a neighbor node of the destination) and a receiver (i.e., destination) participate in the packet delivery. The other neighbor nodes of the destination first try to send the packet but stop forwarding after random backoff and channel sensing. Total energy consumption for a packet delivery is the same between all the destinations, since they are within the one-hop transmission range of the coordinator. Then, the total energy consumption for two senders and a receiver, $E_{SHDP}^{tx}$ and $E_{SHDP}^{rx}$, respectively, is written as

$$E_{SHDP}^{tx} = \left( 1 - (1 - e)^2 \right)$$

$$\times \left\{ \left( 1 - (1 - (1 - e)^2)(N_{ne})^{\varepsilon_{tx,one}} \right) + \left( (1 - e)^2 N_{ne} - 1 \right) \left( \frac{prx_{t}packet}{2} + \varepsilon_{cs} \right) \right\}. \quad(21)$$

$$E_{SHDP}^{rx} = prx_{t}packet + (1 - e) prx_{t}packet$$

$$+ (1 - e)^2 prx_{t}packet$$

$$+ \left( 1 - e^2 \right) \left( 1 - (1 - (1 - e)^2)(N_{ne})^{\varepsilon_{tx,one}} \right). \quad(22)$$

In (22), the first, second, and third terms come from direct packet reception from the destination. The last term comes from the reception of a forwarded packet.
Also, in each transmission, neighbor nodes consume more energy to overhear the packet. Then, energy consumption for overhearing when the coordinator delivers a packet to node $k$, $E_{SHDP}^h$, is calculated as

$$E_{SHDP}^h = N_{tot}P_{rx}^t_{packet} + (1 - e)N_{neighbours}^t_{packet} + t_{ack} + \left(1 - (1 - e)^2\right)^2 \left(1 - \left(1 - (1 - e)^2\right)^N_{neighbours}\right) N_{tot}^t_{ack,one}$$

Here the first term is given by the procedure that all the nodes overhear the high power transmission from the coordinator. The second term is given by the procedure that neighbor nodes which successfully receive the packet overhear packet 0 and receive its acknowledgement. Finally, the last term represents the energy for overhearing the packet forwarded by neighbor nodes.

The total energy consumption by all the nodes with the use of SHDP during the observation time $T$, $E_{SHDP}$, is represented as

$$E_{SHDP} = e_{cs,tot} + N_{packet} \times \left(E_{SHDP}^e + E_{SHDP}^s + E_{SHDP}^h\right).$$

As in the analysis of MHDP, $E_{SHDP}$ has a trade-off in terms of $t_{wakeup}$ due to $e_{cs,tot}$ and $E_{SHDP}^e$. However, $E_{SHDP}^h$ may be much lower than $E_{SMHD}^e(k)$, because SHDP is independent of the network size and a node transmission is required only for failure of the coordinator’s transmission. Thus, the use of low duty cycle (i.e., large $t_{wakeup}$) in SHDP may reduce energy consumption in large scale LLNs, which significantly improves the energy efficiency of the conventional protocol.

V. PERFORMANCE EVALUATION

A. Simulation scenario

The performances of SHDP and MHDP are evaluated through computer simulation using C++. Suppose each node uses transmission power of 0dBm, whereas the coordinator of SHDP uses 17dBm (i.e., transmission power of Wi-Fi). Each node has receiver sensitivity of -87dBm [9]. Then, a coordinator and a node of SHDP cover 191.35m and 58.4m, respectively, with use of path loss model of [10]

$$PL(d) = \begin{cases} 40.2 + 20 \log(d), & \text{for } d \leq 8 \\ 38.5 + 33 \log\left(\frac{d}{8}\right), & \text{otherwise.} \end{cases}$$

Thus, the coordinator can cover a three-hop range of a battery powered node. We consider 100 nodes randomly deployed in the circular area of radius 191.35m where a coordinator is located in the center. Consider the use of offset quadrature phase-shift keying (O-QPSK) modulation defined in IEEE 802.15.4 [9] and used by CC2420. Note that a node in the boundary of the transmission range may receive a packet with a PER of 10% while a node within the transmission range may receive it with a PER less than 10% [11]. Let $p_{tx} = 70mW$, $p_{rx} = 78mW$, $p_{cs} = 30mW$, and $p_{dle} = 3.7mW$ according to CC2420 characteristics [9].

Each node transmits a packet based on BoX-MAC-2 with $t_{bo,max} = 50t_{slot}$ where $t_{slot}$ is the unit backoff period of 0.32ms determined by IEEE 802.15.4 [10]. We assume that the channel sensing range is the same as the transmission range of a node (i.e., 58.4m). We do not consider the capture effect; therefore, a hidden-node collision definitely causes packet errors. A node can retransmit a packet 3 times ($N_{tx} = 3$). The coordinator is assumed to generate a packet every 15s to a randomly selected destination. Since we set the packet size to 50 bytes, $t_{packet} = 5t_{slot}$ with use of the physical layer of IEEE 802.15.4. Assume that $t_{ack} = t_{slot}$. The simulation is conducted for 4 hours.

B. Simulation results

1) Energy consumption: Fig. 2 depicts the energy consumption per node according to the wake-up interval. The energy consumption of MHDP first decreases but increases again as the wake-up interval increases. This is because a large wake-up interval yields heavy transmission burden. Thus, MHDP hardly supports LLNs of low duty cycle due to the energy inefficiency. On the contrary, SHDP consumes lower energy than MHDP, and the energy consumption continuously decreases even when the wake-up interval is long. It is because in SHDP a neighbor node forwards a packet only when the direct transmission of the coordinator fails, which triggers low transmission overhead. It is also observed that analytic results are very close to simulation results. In MHDP, the gap between simulation and analytic results is also within some error.

Fig. 3 depicts energy fairness according to the wake-up interval, using the Jain’s fairness index $J(\varepsilon)$ defined by

$$J(\varepsilon) = \left(\frac{\sum_{i=1}^{N_{tot}} \varepsilon_i^2}{N_{tot} \sum_{i=1}^{N_{tot}} \varepsilon_i}\right)^2$$

where $\varepsilon_i$ is total energy consumption of node $i$. MHDP incurs unfair energy consumption as the wake-up interval increases. Nodes near the coordinator transmit more packets than those far away from the coordinator and the overhead for a packet transmission increases as the wake-up interval increases. Thus, nodes near the coordinator suffer from severe transmission overhead for a large wake-up interval; therefore they consume much greater energy than those far away from the coordinator.

On the other hand, SHDP supports better energy fairness regardless of the wake-up interval. This is because SHDP enables a packet directly to be transmitted to the destination without multi-hop communication. Each node can transmit a packet only when the coordinator fails to directly transmit a packet to its neighbor node, where the same transmission overhead appears throughout all the nodes. SHDP ensures a much longer network life time than MHDP, since SHDP consumes less average energy and at the same time supports fairness for energy consumption.

2) Latency: Fig. 4 depicts the average latency according to the wake-up interval where the red line means inter packet
Fig. 2. Energy consumption as a function of the wake-up interval.

Fig. 3. Energy fairness as a function of the wake-up interval.

Fig. 4. Latency as a function of the wake-up interval.

interval (=15s). Basically, the latency increases as the wake-up interval increases since a node checks the medium infrequently. In particular, the latency of MHDIP sharply increases when the latency is longer than the inter packet interval. It is because a new packet starts to be delivered before the previous packet delivery finishes, thus yielding backoff extensions or collisions. On the other hand, SHDP outperforms MHDIP since SHDP eliminates multi-hop communication and efficiently mitigates contentions among forwarding nodes. Due to the low latency, SHDP can mitigate buffer overflow, and thus, provide better reliability than MHDIP. The simulation results about reliability are omitted in this paper due to lack of space.

VI. CONCLUSION

We have considered a smart use of infrastructure for LLNs. Based on the use of high power for a coordinator in LLNs, we designed a new downlink protocol, SHDP, which eliminates multi-hop communication from LLNs. SHDP comprises direct packet transmission of the coordinator, overhearing of neighbor nodes, local acknowledgement, forwarding of neighbor nodes, and contention mitigation among forwarding nodes. Its performance is evaluated by mathematical analysis as well as computer simulation, which shows that significant performance improvement is achievable compared to the ideal multi-hop downlink protocol, MHDIP. Thus, we conclude that SHDP outperforms any conventional multi-hop downlink protocol. It is also shown that SHDP can support a three-hop range with the use of Wi-Fi power (i.e., 17dBm). SHDP is applicable to automatic price-tag update which requires an efficient downlink framework. Although we have designed only downlink protocol in this paper, we believe that the use of high transmission power at the coordinator may further improve the uplink performance of LLNs. It would also be interesting to extend our work to the cases of interference mitigation and multi-coordinator deployment.

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