TTL-based Efficient Forwarding for the Backhaul tier in Nanonetworks

Hang Yu, Bryan Ng, Winston K.G. Seah, Ying Qu
School of Engineering and Computer Science
Victoria University of Wellington, Wellington 6140, New Zealand
Email: { hang.yu, bryan.ng, winston.seah, ying.qu }@ecs.vuw.ac.nz

***Abstract*—Electromagnetic-based Wireless Nano Sensor Networks (EM-WNSNs) working in the TeraHertz (THz) band are developing fast because of the high sensing resolution that benefits a wide range of applications. In EM-WNSNs, nano sinks that aggregate data from nano sensors to the Internet of Things (IoT) gateway collectively form a backhaul tier of EM-WNSNs. Unlike the data tier composed of densely deployed nano sensors that are closely connected, the backhaul tier consisting of less dense nano sinks is highly vulnerable to the dynamic channel states of THz band that is sensitive to the surrounding humidity change. Thus, a forwarding scheme that adapts to dynamic channel states is needed to ensure both connectivity and efficiency of data transfers over the backhaul. Current channel-aware approaches are based on complex hardware support that cannot be deployed on nano devices due to the size constraints. To solve this problem, the Time-To-Live (TTL)-based Efficient Forwarding (TEFoward) with low complexity is proposed for the backhaul tier of multi-hop polling-based EM-WNSNs. In TEFoward, the functions carried by polling beacons are diversified besides data extraction. Nano sinks select forwarders and direct packets based on the duplicate counts and TTL values of polling beacons which reflect the latest topology information. Demanding lightweight resource support, TEFoward achieves high end-to-end data delivery ratio and energy efficiency.**

I. Introduction

Electromagnetic-based Wireless Nano Sensor Networks (EM-WNSNs) operating in the THz band (0.1 THz - 10 THz) are envisaged to bring high sensing resolution to a wide range of applications [1]. In the EM-WNSNs architecture, nano sinks that aggregate and backhaul the sensed data from nano sensors towards the Internet of Things (IoT) gateway [2] form the backhaul tier which bridges EM-WNSNs to the overall IoT, as shown in Fig. 1.

Unlike nano sensors that are densely deployed with short-range communications, nano sinks have lower density and are expected to communicate over a longer range [3]. THz channels are impacted by molecular absorption caused by environmental factors such as humidity [4]. Consequently, the topology of the backhaul tier becomes dynamic, which demands a data dissemination scheme with channel adaptability for effective and efficient data backhauling. On the other hand, graphene-based nano devices have high sensitivity but low compute, power and memory capacity [5], which limits the ability to adopt precise channel-aware techniques used in traditional micro-scale devices [6] and demands networking schemes with low implementation complexity. Consequently, existing works done for both micro-scale sensor networks and EM-WNSNs could hardly be adopted as solutions due to either the high complexity or the lack of dynamic channel adaptivity. Therefore, a light-weight efficient data dissemination scheme adaptive to dynamic channel states is required for the backhaul tier of EM-WNSNs.

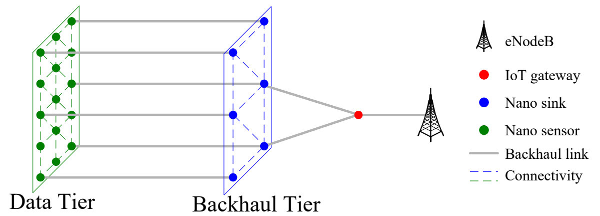


Fig. 1. EM-WNSNs with a dense data tier and a sparse backhaul tier.

To achieve this goal, we propose a low-complexity Time-To-Live (TTL)-based Efficient Forwarding (TEForward) scheme. TEFoward is designed for the scenario where nanonetworks implement data acquisition via multi-hop polling [7]. Specifically, the IoT gateway broadcasts polling beacons periodically to poll nano sinks for data extraction. In TEForward, the polling beacons have multiple functions. In each polling interval, nano sinks extract the duplicate count and TTL values to infer the latest network topology information to narrow the set of forwarders and direct data flows. TEForward achieves forwarding with high data delivery ratio and energy efficiency under dynamic channel states with repurposing of polling beacons.

The rest of the paper is organized as follows. The background of THz channel modeling and related work on data dissemination for EM-WNSNs are reviewed in Section II. The design details of TEForward are presented in Section III. The performance of TEForward is modeled, evaluated and analysed in Section IV. Conclusions are in Section V.

II. Background and Related Work

A. Molecular Absorption in the THz band

Data transmission in the THz band communications may incur significant path loss due to the molecular absorption. The path loss of THz band A_T is jointly influenced by the free space path loss A_S and the molecular absorption loss A_{abs} [8], as follows:

$$A_T(f,d) = A_S(f,d) \cdot A_{abs}(f,d) = \left(\frac{4\pi df}{c}\right)^2 \cdot e^{K(f)d}, \quad (1)$$

where c is the speed of light $3 \cdot 10^8$ m/s, f is the frequency, d is the transmission distance, $K(f)$ is the molecular absorption coefficient [9], k_B is the Boltzmann constant and T_0 is the reference temperature 296K.

The molecular absorption caused by humidity is dominant for long-distance transmission. Therefore in nanonetworks communicating over the THz band, overcoming the impairments of dynamic channel states caused by humidity is a significant challenge.

B. Data dissemination in EM-based Nanonetworks

Data dissemination schemes for data delivery in micro-scale sensor networks [10] have been extensively studied; however they are not suitable for EM-WNSNs due to the channel characteristics and hardware limitations. Therefore, we focus on data dissemination schemes proposed for EM-WNSNs.

Initially, centralized schemes were preferred because these schemes shift the computation burden from low-capacity nano sensors to nano sinks. This motivated a routing framework [3] for energy efficiency. Before each transmission by a sensor, the nano sink evaluates the energy efficiency of the single-hop mode and the multi-hop mode by calculating the Critical Neighbourhood Range (CNR) and the Required Transmission Power (RTP). Then, the nano sensor transmits via the mode that consumes less energy.

Another two energy-oriented routing schemes, namely the optimal/greedy energy-harvesting aware routing [11], are proposed for body-area nanonetworks. Routing decisions are made to achieve cluster-level/node-level energy efficiency respectively.

Targeting end-to-end channel capacity in multi-hop transmissions, the channel-aware forwarding [12] is proposed. For each transmission, the nano sink selects the forwarding candidate for the transmitting node based on a forwarding metric that considers both the THz channel capacity and delay.

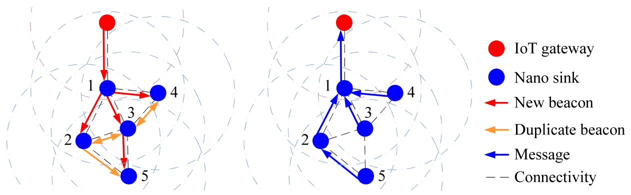
Envisaging the future status of nano devices, distributed lightweight schemes that reduce networking overhead have become the recent research trend. Selective flooding and random routing [13] are two simple routing algorithms proposed for EM-WNSNs. In selective flooding, packets are flooded through the network with duplicate removal to achieve high packet delivery ratio and bandwidth efficiency. In contrast, the random routing randomly selects one of the neighbours to forward data for high energy efficiency. These two schemes show the huge tradeoff between packet delivery and energy consumption.

Two more advanced data dissemination schemes proposed for Software Defined Materials (SDM) are the lightweight self-tuning data dissemination [14] and CORONA [15]. The lightweight self-tuning data dissemination is a receiver-based routing scheme. For each transmission, the sender simply broadcasts its packet. The receiver that receives the packet decides whether to join the forwarding process based on a metric calculated from its number of successful receptions. To make the data dissemination more efficient, CORONA, a GPS-free geographic routing is first applied in nanonetworks. Nodes use the coordinated hop-count information provided by four anchor nodes to infer their geographic locations. After that, packets are routed based on the minimal hop-count principle.

The existing works have investigated data dissemination for EM-WNSNs under static channel conditions while research done for the backhaul tier of nanonetworks with relatively large coverage subjected to dynamic channel conditions remains sparse. In this case, data dissemination schemes that adaptively respond to dynamic channel states are needed.

III. Proposed Solution

In this section, the design of the proposed low-complexity TTL-based efficient forwarding is discussed. The pseudocode of TEFoward is shown in Algorithm 1 and Fig. 2 with notations explained in Table I.



(a) Beacon dissemination (b) Message forwarding

Fig. 2. Data Dissemination of TEForward.

Algorithm 1 TTL-based Efficient Forwarding

For each nano sink:

if receives a new polling beacon $Beacon$ **then**
  $TTL_S = TTL_{\max} - TTL_P$
  Set $N_S = 1, CumN_F = CumN_P$, $FID_S = SID_P$
  for each duplicate of $Beacon$ **do**
    $N_S{+}{+}$
  if $CumN_F > CumN_P$ **and** $TTL_S = TTL_P{+}1$ **then**
    $CumN_F = CumN_P$
    $FID_S = SID_P$
  end if
  Drop duplicate beacon
  end for
  Set $CumN_P = CumN_F + N_S$
  Broadcast $Beacon$ with $TTL_P{-}{-}$
  Aggregate and send M_{pkt} to FID_S
else if receives a new message packet M_{pkt} **then**
  if this packet is for me **then**
    Forward M_{pkt} with $TTL_P{-}{-}$ to FID_S
  end if
end if

The key concept of the TEForward is to leverage the polling beacons to obtain the latest network topology information

TABLE I
NOTATIONS USED TO DESCRIBE ALGORITHMS

Notation	Description
$Beacon$	A beacon packet
M_{pkt}	An aggregated message packet
TTL_S	The TTL setting of a nano sink
TTL_P	The TTL value of a packet
TTL_{max}	The maximal value of TTL
N_S	The neighbour-size indicator of a nano sink
$CumN_F$	The cumulative neighbour size of a potential forwarder
$CumN_P$	The cumulative neighbour-size field of a packet
x	The size of $CumN_P$ field
FID_S	The ID of the selected forwarder of a nano sink
SID_P	The MAC source ID of a packet

PHY	MAC	NET	$CumN_P$

Fig. 3. Structure of a polling beacon.

under dynamic channel states for forwarder selection and data diffusion. As shown in Fig. 2 (a), for each polling, the IoT gateway floods a polling $Beacon$ that has packet format as shown in Fig. 3 with TTL value of TTL_{max} for data extraction.

Besides original fields of a packet header [13], the polling beacon in TEForward adopts one new field $CumN_P$, whose size x depends on the network size, to store the cumulative neighbour size of forwarders along a path. $CumN_P$ represents the total number of nano sinks that will be receiving message packets during data delivery, indicating the end-to-end energy consumption caused by the packet reception process. $CumN_P$ is set to 0 by the IoT gateway and updated by nano sinks to cumulate local neighbour sizes during the beacon flooding.

All nano sinks that receive a new $Beacon$ first align their TTL settings TTL_S based on the TTL value of the beacon packet TTL_P as in Algorithm 1 step 2 to obtain their distances from the IoT gateway in number of hops. Next, following step 3, nano sinks reset the local neighbour size N_S and initialize the local variable $CumN_F$ with $CumN_P$ in $Beacon$. For each nano sink, $CumN_F$ plays a significant role in forwarder selection since it is used to identify the forwarder which directs packets along the path that triggers the smallest number of packet receptions.

In steps 4–11 of Algorithm 1, by receiving a duplicate of $Beacon$, the nano sink increments the local neighbour size N_S and updates its potential forwarder. Specifically, the nano sink compares the value of TTL_S with TTL_P and the value of $CumN_F$ with $CumN_P$ to check if the beacon duplicate comes from a sink that is located towards the IoT gateway and provides a path with higher energy efficiency than the last forwarding candidate. If so, the nano sink selects the beacon sender as its forwarder by recording the MAC source ID of the duplicate beacon. The duplicate beacon is then dropped. One example of the forwarder selection is depicted in Fig. 2 (b) whereby "Nano sink 5" selects "Nano sink 2" as its forwarder rather than "Nano sink 3" because the cumulative neighbour size of "Nano sink 2" is lower than that of "Nano sink 3", which mitigates the number of nano sinks involved in packet reception during the end-to-end data delivery. The final forwarder selected will direct packets towards the IoT gateway with high energy efficiency because of the minimized number of nano sinks activated for packet transmission and reception.

Then, in step 12, the up-to-date cumulative neighbour size, which equals the sum of the cumulative neighbour size of the selected forwarder $CumN_F$ and the local neighbour size of the current sink N_S, is placed in the $CumN_P$ field of $Beacon$ which is then forwarded. Ultimately, the nano sink aggregates packets from nano sensors and sends the aggregated packet M_{pkt} to the selected forwarder FID_S. Sinks that are involved in packet forwarding will forward this message packet to their own selected forwarder as in steps 15–19 until it reaches the IoT gateway. In this way, all message packets are effectively and efficiently directed to the IoT gateway along the latest efficient path of the polling moment.

For each nano sink, the time complexity of TEForward algorithm is $\mathcal{O}(N_S)$. Compared with existing works, the merits of TEForward are: 1) feasible implementation for nano devices as TEForward implements major networking functions assisted by polling beacons, thus has low resource demands and fits the device capacity of nano devices with μm-level dimensions [1]; and 2) requiring no hardware supports beyond nano devices, TEForward provides the first solution of data dissemination that considers dynamic environment impact for the backhaul tier of polling-based EM-WNSNs.

IV. PERFORMANCE EVALUATION

In this section, the performance of TEForward is modelled, evaluated and analysed against benchmark schemes.

A. Performance Metrics

In this paper, the proposed TEFoward is evaluated based on the following performance metrics:

1) Packet delivery ratio, PDR:

$$PDR = \frac{N_R}{N_T}, \tag{2}$$

where N_R is the total number of unique packets received by the IoT gateway, and N_T is the total number of unique aggregated message packets transmitted by nano sinks for one polling.

2) Collision probability, P_{COLL}:

$$P_{COLL} = \frac{N_{COLL}}{N_{RX}}, \tag{3}$$

where N_{COLL} is the total number of collision and N_{RX} is the total number of packet receptions during the end-to-end data delivery for one polling.

3) Delay, D:

$$D = T_{RX} - T_{TX}, \tag{4}$$

where T_{RX} is the time when a packet is received by the IoT gateway, and T_{TX} is the time when this packet is sent by the nano sink.

4) Energy Consumption of polling one packet, E:

$$E = E_T + E_R, \tag{5}$$

where E_T and E_R are the total energy consumed by transmitting and receiving packets during data delivery for polling one packet, respectively. Specifically, for each bit, the energy consumed by receiving is 10% of the amount consumed by transmitting [16].

5) Forwarder count, F_{count}: the number of forwarders for each transmission during data delivery

$$F_{count} = \frac{N_F}{N_P H}, \tag{6}$$

where N_F is the total number of forwarding, N_P is the number of message packets polled, and H is the average hop count during the end-to-end data delivery for one polling.

6) Cumulative receiver count, CR_{count}: the total number of nano sinks involved in packet reception during the end-to-end data delivery for one message packet polled

$$CR_{count} = \frac{N_{RX}}{N_P}, \tag{7}$$

where N_{RX} is the number of packet receptions occurring during the end-to-end data delivery for one polling.

B. Benchmarks

To benchmark the performance of TEForward, a simple TTL-based Efficient Flooding (TEFlood) is proposed as presented in Algorithm 2. In TEFlood, nano sinks align the TTL settings of their message packets based on polling beacons and forward message packets only when they are located closer to the IoT gateway than the sender to minimize the flooding area. Besides, the selective flooding (S-Flooding) [13] introduced in Section II-B is also involved in performance comparison.

C. Simulation Setup

The performance of TEForward is evaluated using the nano-sim [13] package of NS3. Simulation settings are shown in Table II. The 100-fs-long Gaussian pulse with 1 pJ energy [16] on 1 THz is adopted for one bit transmission. A message packet is 136 bits long composed of 100-bit payload and 36-bit overhead with an initial TTL of 100 [13]. Statistically, we assume that the average ratio of bit "1" in a packet is 50% [16] when evaluating energy consumption. Considering the property of graphene [1], the receiving sensitivity for packet reception is set by expectation as researchers do in a recent work [14]. The simulated area is set to 10m $\times$ 10m wherein one IoT gateway is placed in the centre and from 10 to 100 static nano sinks are uniformly distributed so that the network connectivity transits from low to high. The corresponding size of field $CumN_P$ is set to 10 bits. Considering the energy capacity of nano nodes, the simulation lasts for 600s with a polling interval of 60s and a nano sink aggregates 10 packets for each polling. As shown in Fig. 4, the dynamic channel state in simulations is implemented by a time-varying sinusoidal-based molecular absorption coefficient K for 1 THz. The minimum and maximum of K represent channels containing 1% and 20% water vapour, respectively.

Algorithm 2 TTL-based Efficient Flooding

For each nano sink:

```
if receives a new polling beacon Beacon then
    TTL_S = TTL_max − TTL_P
    Broadcast Beacon with TTL_P −−
    Aggregate and broadcast M_pkt with TTL = TTL_S
else if receives a new message packet M_pkt then
    if TTL_S < TTL_P then
        Broadcast M_pkt with TTL_P −−
    end if
end if
```

TABLE II
SIMULATION PARAMETERS

Parameter	Value
Frequency	1 THz
Pulse energy	1 pJ
Pulse duration	100 fs
Receiving sensitivity	-130 dBm
$CumN_P$ field size	10 bits
Unit packet size	136 bits
Beacon packet size	46 bits
Packet aggregation size	10 packets
TTL_{max}	100
Simulation area	10m $\times$ 10m
Network size	10,20,30,40,50,60,70,80,90,100 nano sinks
IoT gateway position	Centre
Nano sink position	Uniformly distributed
Nano sink mobility	Static
Simulation duration	600s
Polling interval	60s

Performance of TEForward is evaluated and compared with TEFlood and S-Flooding via the metrics in Section IV-A. Each result presented is the average with 95% confidence interval obtained from 50 simulations with different seed values.

D. Numerical Results and Analysis

The simulation results of packet delivery ratio, collision probability, average delay, total energy consumption, forwarder count and cumulative receiver count are presented in Fig. 4 to Fig. 15 for different networks sizes and time-varying channel states. We only compare the energy efficiency of TEForward with TEFlood for the sake of clarity because the S-Flooding will have huge energy consumption (and thus yield graphs that obscure interesting observations).

1) Packet delivery ratio: As shown in Fig. 4 and Fig. 5, packet delivery ratio highly depends on node density that is related to the molecular absorption coefficient K in Equation 1 and the network size. Specifically, for a low K or a high network size, packet delivery ratio deteriorates due to collisions as a consequence of the high node density. TEFoward achieves high packet delivery ratio with a difference of less than 0.4% in comparison with TEFlood and S-Flooding. This is benefited from the Time Spread On-Off Keying (TS-OOK)

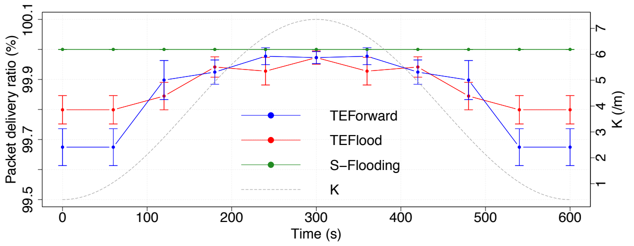


Fig. 4. Packet delivery ratio vs time

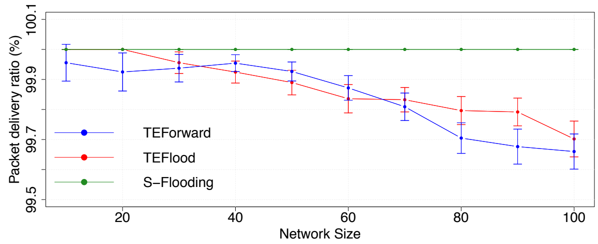


Fig. 5. Packet delivery ratio vs network size

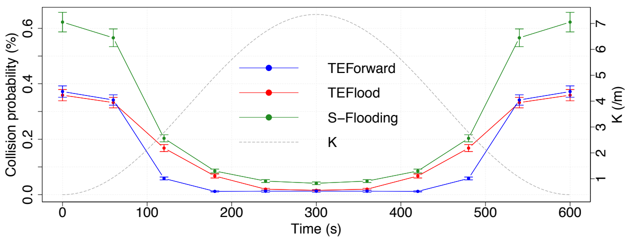


Fig. 6. Collision probability vs time

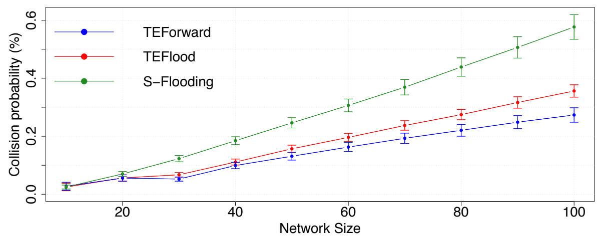


Fig. 7. Collision probability vs network size

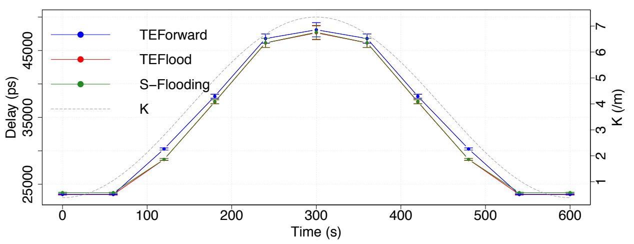


Fig. 8. Delay vs time

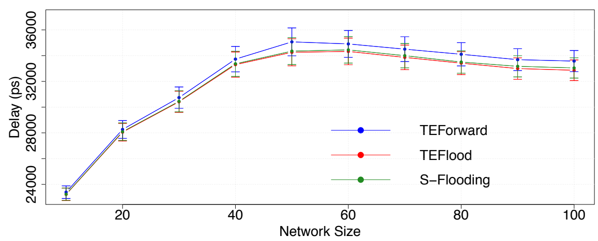


Fig. 9. Delay vs network size

[8] modulation with low collision probability of EM-WNSNs. While S-flooding always shows 100% packet delivery ratio, the energy cost of this scheme is high.

2) Collision probability: From Fig. 8 and Fig. 7, TEForward has the lowest collision probability because of its minimized number of nodes involved in packet forwarding and reception. The S-Flooding scheme suffers from high collision probability due to the large flooding area especially for high node density caused by low K or high network size.

3) Average delay: Delay is directly proportional to the hop count of packets and network connectivity. In Fig. 8, the increased delay is a result of the high molecular absorption K leading to increased hop count. In Fig. 9, the low delay for small network sizes is a result of poor connectivity which only allows sinks nearby the IoT gateway to be polled. When connectivity rises, the chance of having forwarders geographically close to the gateway at each hop increases, which then decreases the end-to-end delay. TEForward shows slightly inferior performance to TEFlood and S-Flooding due to its criteria of forwarder selection that prioritizes end-to-end energy efficiency, which might miss the forwarder with low latency, such as nano sink 3 in Fig. 2 (b).

4) Total energy consumption: From Fig. 10 and Fig. 11, as expected, TEFoward shows high energy efficiency because of the small number of transmissions and receptions during data delivery. As shown in Fig. 12 to Fig. 15, for each polling, TEForward only triggers one forwarder in each hop and guides the packet towards the IoT gateway along a path with the fewest passive receivers. In contrast, the multicast feature of TEFlood results in more packet processing especially when the end-to-end hop count increases with a magnitude much higher than the decrease of node density, like the results at 120s and 480s in Fig. 10, Fig. 12, and Fig. 14.

Summarizing the simulation results, by extracting the latest topology information from polling beacons, the proposed TEForward achieves high data delivery ratio and energy efficiency under dynamic channel conditions.

V. Conclusion

In this paper, a TTL-based Efficient Forwarding (TEForward) scheme is proposed for the backhaul tier of multi-hop polling-based EM-WNSNs under dynamic channel states. The TEForward extracts the up-to-date topology information from polling beacons for forwarder selection and data diffusion with low overheads. Following the forwarding decisions of TEForward, all packets flow to the IoT gateway along the path with the minimum energy consumption determined at the moment of polling. From performance evaluation, TEForward is proven to achieve high data delivery ratio, high energy efficiency and low collision probability.

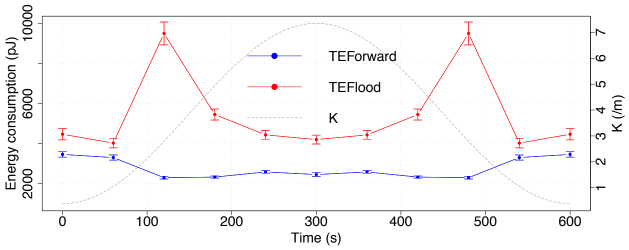


Fig. 10. Energy consumption of polling one packet vs time

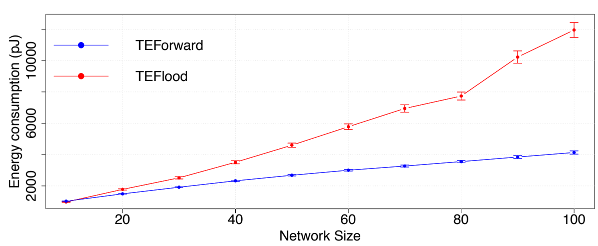


Fig. 11. Energy consumption of polling one packet vs network size

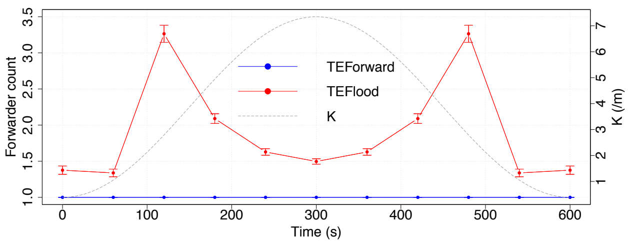


Fig. 12. Forwarder count vs time

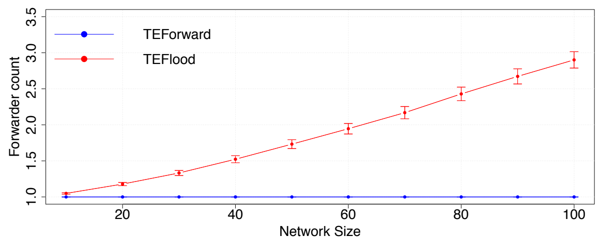


Fig. 13. Forwarder count vs network size

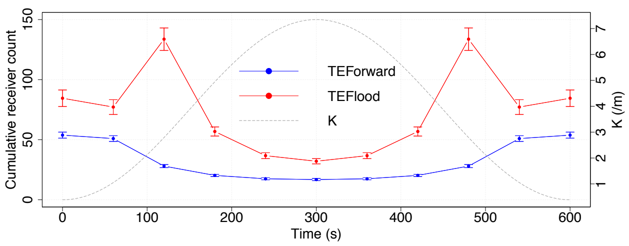


Fig. 14. Cumulative receiver count vs time

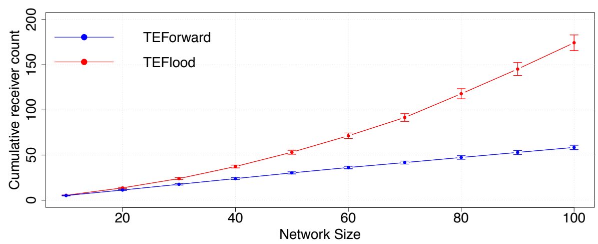


Fig. 15. Cumulative receiver count vs network size

VI. Acknowledgement

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