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Multi-objective optimisation for selective packet discarding in wireless sensor network

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Abstract: Traffic convergence in wireless sensor networks (WSN) during simultaneous data transmission may overwhelm its limited buffer capacity, resulting in congestion, waste of resources and severe performance degradation. The obvious consequences include high packet loss rate, huge amounts of wasted energy and obsolete data that may lead to inaccurate information. Since WSN suffers from scarce resources such as energy, data transmission which is the main cause of energy depletion should be kept to the very minimum. Various studies have used packet discarding as a means to reduce high traffic volumes. However, none of these methods have ever been applied in WSN which possesses different characteristics. This study proposes a new technique for mitigating congestion by selectively discarding some of the least important packets to give sufficient room for more important ones to get through. The proposed discarding policy is integrated with multi-objective optimisation (MOO) which can optimise several objectives at once. The proposed selective packet discarding policy discards the unimportant packets based on some discarding criteria which will be optimised by the MOO. Performance evaluation using the optimisation tool (LINGGO) and simulation in Network Simulator 2 shows remarkable and promising performance with more than 50% improvement.

1 Introduction

With the possibility of multimedia data and bio-signals being transported over the sensor networks, huge amounts of traffic is likely to be a common scenario, leading to inevitable problems with congestion, especially during simultaneous data transmission. This worsening situation in wireless sensor network (WSN) requires a robust technique to handle critical consequences that may affect the performance and interfere with seamless data transmission during congestion. Congestion in WSN may cause various problems, such as loss of important packets in emergency situations, causing delays that may lead to outdated information and wasting a lot of useful resources that may otherwise be used to transfer more important packets.

Congestion is a well-known resource-sharing problem which is becoming a major problem in WSN. This normally occurs during simultaneous packets convergence across multiple nodes. The limited buffer in WSN makes managing the incoming traffic even more challenging. A congestion scenario is illustrated in Fig. 1*a*. A substantial number of packets may not be able to fit into the small amount of spaces in the WSN buffer, hence causing some packets to be dropped. These may include important packets, carrying meaningful translations for the end systems.

1.1. Problem statement

The loss of important packets in WSN will affect the performance of the whole system in many ways. Firstly, it will increase the number of retransmissions which is too costly for the scarce and limited resource systems like WSN. As the number of retransmissions increases, so does the energy consumption to retransmit the lost packets. Since the nodes in WSN suffer from having limited energy, bandwidth (bw), memory and processing power, retransmitting the lost packets is too costly since it incurs additional energy and bw, thus wasting valuable resources.

Secondly, retransmission processes also result in high end-to-end delays. Consequently, the mean waiting time also increases. This is unacceptable for the delay-sensitive and real-time applications which require delays to be below certain boundaries. Thirdly, the high end-to-end delay corresponding to retransmission processes may result in massive reductions in packets' lifetime, hence increase the staleness level of associated packets. Obsolete packets are not useful by the time they reach their destinations. This may affect the decision-making process which can lead to false action. In cases of emergency in healthcare applications, obsolete packets may lead to wrong diagnoses.

Such scenarios can be minimised if the incoming packets are handled properly by selectively discarding some packets to free up spaces in the buffer. The generic illustration of

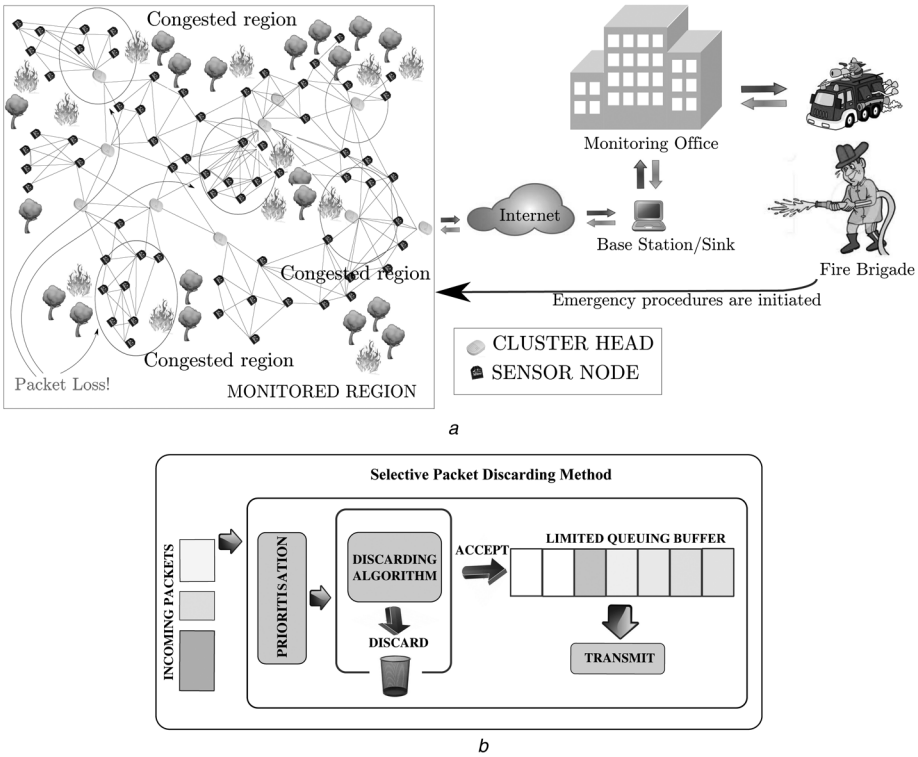

Fig. 1 *Congestion scenario*

a Congestion scenario in WSN that will cause a massive number of packet losses as shown by the arrows This is where packet dropping policy may help to improve the performance of the affected system
b The conceptual view of the SPD approach to reduce the number of packets and thus avoid congestion

selective packet discarding (PD) approach can be seen in Fig. 1*b*. In this approach, some unimportant packets will be discarded, giving sufficient space to transmit more important ones.

1.2 Existing approaches and limitations

Several solutions have been engineered to cater congestion problem in many different areas [1–3]. The most common method is PD [4–9] which discards some packets to reduce the amounts of traffic. The simplest form of PD technique known as drop tail (DT) simply drops all packets that arrive upon a full buffer, hence result in very low throughput. Partial PD (PPD) [10, 11] and Earlier PD (EPD) [12–14] have been developed to further enhance the received throughput in DT. Although PPD can improve throughput, it suffers from fairness issue. This problem has been tackled in EPD, with the cost of performance degradation in multi-hop networks. Further improvement is proposed in SPD [15–17], but no optimal performance is ensured.

1.3 Objective of the research

This research mainly focuses on a method to avoid losing important packets in inevitable conditions which require some packets to be dropped because of congestion. Some of these packets might be important for translation at end systems. Therefore their loss will be harmful to victims in the underlying applications. As well as achieving that objective, this research also aims at providing optimum performance in ensuring the best possible solution of PD. This is because of the very challenging decision making affected by several selection of discarding criteria.

1.4 Proposed solution

In achieving the defined objectives, we integrate SPD mechanism with multi-objective optimisation (termed as SPD-MOO). First, we define several discarding criteria to maintain WSN performance. Issues such as 'duplicate packets, number of hops traversed and packets lifetime' are among important factors to be considered. Next, we formulate necessary objective functions (OF) that need to be simultaneously optimised to achieve optimum result.

The novelty of the proposed technique relies on the multi-objectives optimisation that can assist to achieving optimum performance. This is also to ensure the right decision in discarding process so that the system can afford to transmit only packets that deserve the transmission. The implementation of the existing SPD policies have never acknowledged the significant of any packets to a system. Hence, the act of discarding any packets during congestion may jeopardise and degrade the entire performance. This is starkly in contrast with our proposed method which takes into account several criteria in determining which the less important packets and accept the important ones deserve for transmission.

1.5 Contributions

The significant contributions of this paper are summarised as follows.

- Proposed a novel congestion avoidance technique in WSN using SPD. As the name implies, the proposed SPD selectively drop the packets that are the least significant to the associated systems. Packets are discarded based on certain criteria. The main objective is to give extra room for

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more important packets so they can be directly transmitted to the sink node for immediate action.

- The novel contribution of our proposed method can be seen in the incorporation of the SPD with MOO. In this case, the MOO is employed to support high quality of service (QoS) assurance by optimising the options of which packets are to be discarded, thus the obtained results are in the highest optimisation states.

The advantages of using MOO is two-fold. It not only provides the optimal solution for SPD but also ensures zero conflict while optimising multiple functions. Therefore this SPD-MOO features a simultaneous optimisation technique that satisfies multiple OF, leaving WSN at the optimum state. The integration between SPD and the MOO in this scheme is named SPD-MOO and the term is used for the rest of the paper.

The rest of the paper is organised as follows. The next section discusses some of the important related works while Section 3 explains the SPD concept and includes a brief discussion of the selected discarding criteria. The MOO is presented in Sections 4 and 5. Performance metrics are presented in Section 6. All the results and analyses are presented in Sections 7 and 8 concludes the paper.

2 Related work

An obvious solution to cater for those issues is to reduce the amount of data aggregated at each node, so that buffers are not overloaded [18, 19]. Among several well-known traffic reduction techniques, PD is the most common and useful method [20].

Most PD techniques mainly focus on asynchronous transfer mode (ATM) [7, 8], heterogeneous networks [9], personal communication networks, video streaming [4, 21, 22], high-speed networks [5, 6, 23] and multi-hop networks [24], but none were used in WSN.

Typical PD includes DT [25, 26], EPD [12–14] and PPD [10, 11]. DT is the simplest discarding technique as it drops all packets that arrive upon a full buffer. This method has the lowest throughput. PPD is introduced to improve the corresponding throughput by discarding all packets that belong to a cell that has already been discarded. However, this technique only discards half of the corrupted packets. Then the EPD is employed to further improve the entire throughput. This is done by discarding entire packets when congestion is detected or when the packets reach a certain threshold. Although this can improve throughput, all these EPD policies suffered from lack of fairness (except EPD, which is not suitable for multi-hop networks), which cause created the SPD.

One of the enhancements over DT is known as random early discard (RED) [27–29] which addresses the unfairness issue by anticipating average buffer size and queue length as a congestion indicator. Although RED has resolved the fairness issue in DT, its basic operation that randomly marks and discards packets to avoid congestion, does not protect the packets that deserve transmission. Further improvements of RED is MRED [30, 31] which considers extra parameters for dropping probability. However, these extra parameters are still insufficient to handle network congestion.

Several other PD approaches developed for wireless networks [1–3], cannot be directly applied to WSN which has different characteristics. In addition, WSN possesses a unique topology in which nodes are randomly scattered in an area to be monitored. Most of the PD methods are designed to cater for the problem in uniformly distributed nodes. Nodes in WSN are also battery powered and subject to other limited resources. These nodes always generate massive amounts of packets in a continuous manner. Therefore managing huge amounts of data in this domain is very challenging and requires a robust mechanism that can intelligently select which packets are to be transmitted and which are to be discarded. Therefore all the existing mechanisms are not suitable for use in congestion control in WSN.

However, uniquely differentiated from the standard PD policies, this paper focuses on the use of the SPD mechanism to tackle congestion issues in WSN. A few attempts at alleviating congestion using SPD have been made [15–17] and favourable performances have been obtained. SPD has been proved to eliminate the fairness issue [32]. Congestion in SPD is controlled by selectively discarding packets based on certain pre-defined criteria so that the amount of traffic can be reduced during simultaneous data transmissions.

Despite the advantages offered by SPD, no optimal solution is provided in any of the previous studies and none of the techniques have been used to solve congestion issues in WSN. Inspired by these limitations and the promising features shed by SPD in the previous techniques, in this paper, we propose a unique SPD method which is characterised by several OF so that multiple objectives can be optimised using MOO. Using this approach, the least important packets are discarded to give sufficient room for the important ones. In this paper, we refer to the least important packets having the lowest interest to the system. This reflects the packets that are identified as not worth transmission based on the outlined criteria. For instance, corrupted packets which contain erroneous bits do not deserve transmission since they will lead to wrong translation to the end system. This can be seen as just wasting time, energy and bw during transmission. This type of packet is considered unimportant to the system and can be discarded. The omission of these packets may not adversely impact the overall performance. Detailed discussion on this can be found in Section 3.

To the best of our knowledge, although SPD has been the subject of research for over a decade, the use of SPD for congestion control in WSN is still considered to be green research and unexplored. Most of the issues solved in WSN only focus on other issues such as coverage, fault detection, power management, energy efficiency, routing, timely data delivery and security [33–35].

3 Proposed selective packet discarding

SPD is a mechanism to alleviate congestion in the condition of heavy network traffic. By definition, SPD is a process of managing the input to the buffer so that sufficient space can be accommodated to the excess arriving packets in reaction to congestion [36]. The goal is to prioritise traffic and give priority to the packets having more importance to the system and discard the less important ones. Heavy traffic during emergency and simultaneous data transmission in WSN may overload the buffer and result in severe performance degradation. In the absence of SPD, packets that arrive at the full buffer will have no option but to be discarded. In contrast, using the SPD, all incoming packets

Algorithm 1:

```
Require: Arrival Rate λ, Packet Size (bytes), Number of Hops;
Obtain the Arrival Rate ⟶ λ ;
if (Hops == Few) then
    if (PacketSize == Small then
        Packet = DROP!;
    else
        if Packets == ErrorFree then
            if Packets ! = DuplicatedPacket then
                Packet = ACCEPT;
            else
                Packet = DROP!;
        else
            Packet = DROP!;
else
    if (PacketSize == Big then
        Packet = DROP!;
    else
        if Packet'sLifetime > transmissionTime then
            if Packets == ErrorFree then
                if Packets ! = DuplicatedPacket then
                    Packet = ACCEPT;
                else
                    Packet = DROP!;
            else
                Packet = DROP!;
        else
            Packet = DROP!;
```

Fig. 2 *Before Traverse*

are intelligently handled by discarding some insignificant packets to give more room for the important ones. This is done by selectively identifying the less important packets based on certain pre-defined criteria. These criteria are discussed in Section 3.3. The selection of the criteria in our approach has been made possible using MOO.

All the procedures involved can be best presented in Figs. 2 and 3. These algorithms can be divided into two: before and after the hops traversed, respectively. There are slightly different policies in implementing the proposed discarding policy, depending on whether the packets have already travelled or are about to travel to the dedicated nodes.

3.1 Reasons for packet discarding

The concrete reasons for performing SPD in WSN can be listed as follows.

- Their loss will not be notable. This is because all the packets that have been selected for discarding are those that have the very least significance to the associated system and that the absence of these packets may not create substantial difference in the expected performance. Examples include duplicated and corrupted packets. Permanently discarding or postponing them for later transmission are rather the best possible options to reduce the amount of traffic and thus prevent a drop in service quality.
- Queuing delays are inevitable, especially during congestion. This situation will create a notable gap in applications that run in real-time and are very sensitive to either delay and loss. Packets experiencing unacceptable delays will be discarded after a certain threshold. This seems a better option since the information received might be obsolete and have a very-low level of validity. In addition, discarding these packets may give extra spaces to quickly dispense the fresh data to their destinations.
- For many applications, if one bit in a packet is lost, the whole packet needs to be discarded and retransmitted for reliability purposes. Transmitting corrupted packets may only waste extra bw and energy besides increasing the chances of congestion. Thus, packets with any single corrupted bit should be discarded to improve performance. Detecting corrupted packets is done using the built-in protocol in Network Simulator 2 (NS-2) known as 'Error Model' via 'corrupt' method [37]. The existence of these packets can be traced in the 'tracefile' using 'Awk' script.
- Discarding the less important packets may vacate more rooms in the buffer and thus permit more important packets to have a better chance of arriving at the destinations in a timely manner. The level of importance of the packets is determined by whether the packets are worth transmission

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Algorithm 2:

```
Data: Arrival Rate λ, Packet Size (bytes), Number of Hops
Obtain the Arrival Rate ⟶ λ ;
if (Packets == Obsolete) then
    if (Packets == ErrorFree then
        if (PacketSize == big) then
            if Packets ! = DuplicatedPacket then
                Packet = ACCEPT;
            else
                Packet = DROP!;
        else
            Packet = DROP!;
    else
        Packet = DROP!;
else
    Packet = DROP!;
```

Fig. 3 *After Traversed*

based on many different scenarios. Less important packets are defined as packets generated within close time-stamp proximity (duplicates), packets that contain insufficient time-to-live (TTL) and packets that may be transmitted in a link that has high error rates. Transmitting these packets will jeopardise the performance of the whole network. Therefore discarding these packets can be seen as the best option to maintain high QoS. The decision to discard these packets may also depend on various scenarios such as the size of the corresponding packets and the number of hops to be traversed.

3.2 Meeting the objectives

In order to perform the proposed SPD, several objectives have to be met.

- To reduce the number of packet loss during simultaneous data transmissions. This can be avoided by discarding some unimportant packets before transmission so the amount of traffic is reduced.
- To preserve the lifetime of packets. This could be done by discarding packets that have little chance of survival or minimal TTL. If delivery across the network takes longer than the packet's lifetime, the packets become obsolete. Transmitting stale data will waste huge amounts of resources and delay the transmission of packets containing fresh data.
- To minimise the number of retransmissions caused by three factors: 'packets getting dropped because of buffer overflow, packets lost because of busy channels, and the occurrence of stale packets or the reduction of a packet's lifetime because of long retransmission delays'. The reduction in the number of retransmissions will automatically reduce the consumption of other resources (bw, energy and transmission time) and prolong packets' lifetimes.
- To reduce transmission delay caused by transmitting unnecessary packets. This can be achieved by reducing the number of packets that are not worth transmitting (e.g. stale data, corrupted data and so on). Achieving this objective also help to avoid the expiry of packets before reaching the destination.

3.3 Discarding criteria

We have characterised several important criteria as discarding factors in order to achieve the aforementioned objectives. There are four main factors.

- *Duplicate packets*. Duplicate packets generated within close proximity of the time-stamp [38]. These packets may duplicate one another and transmitting them all will not only waste time, but also other resources which are limited in WSN. Instead, only one packet which resembles those similar packets and carries the same information will be transmitted.
- *Number of hops to traverse/traversed*. If the number of hops to be traversed are few, then discard the smaller packets and accept a big one. This is because discarding these packets may not cause any notable delay to the applications, while accepting big packets is ideal since they will have fewer chances of being corrupted in the small number of hops. If the number of hops to traverse is large, then bigger packets have to be dropped since there will be few chances of survival and packets may easily get corrupted. These are the packets that are not worthwhile to transmit and will just waste colossal amounts of resources. If the packets have traversed many hops, then we should accept the big packets that contain no errors. This is because discarding these packets may waste the already-consumed resources and also transmission time. Small packets can then be discarded since their loss will only cause least performance degradation.
- *Packets that have very-low expected lifetime*. These packets will not survive before they reach the final destination. In such situations, the packets that have a very-low expected lifetime TTL which is lower than the estimated time to reach the destination, should be discarded since they will not survive transmission. The TTL of each packet is determined when each of the sensor node sets the TTL field in the packets they are sending [39]. Then, each

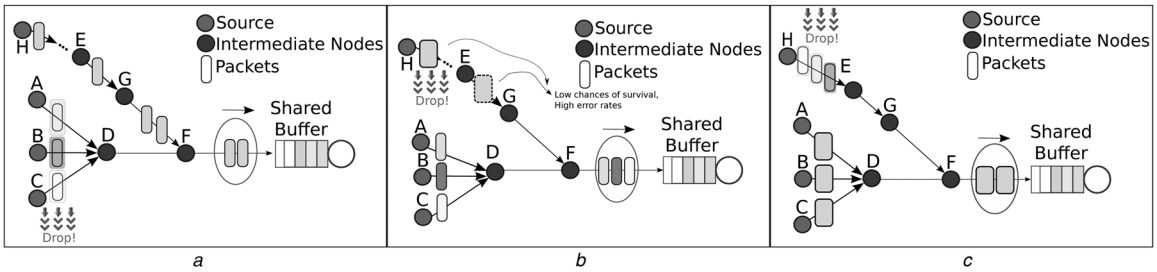

Fig. 4 *Packets dropping scenarios before traversing towards the sink node*

a If a small packet has to travel to many hops, accept the packet if it contains no errors and is not a duplicated packet
b If big packets have to travel many hops, drop the packets before initiating any transmission as they will not survive till the last node
In this case, the small packets that will only be travelling few hops will be accepted
c If big packets have to travel only a few hops, accept the packets and reject the small ones that have to travel many hops

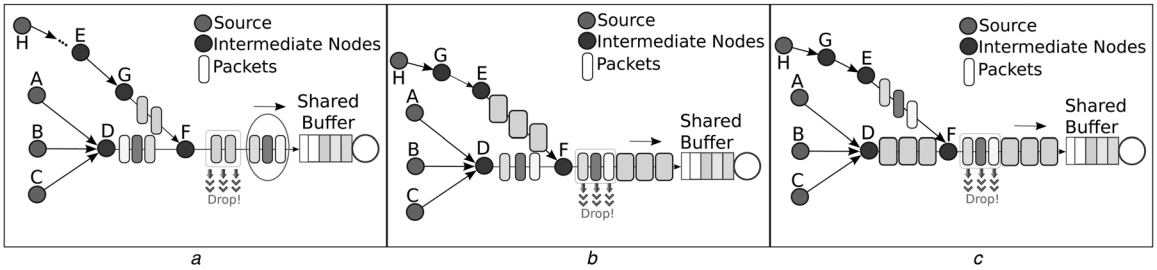

Fig. 5 *Packets dropping scenarios after traversing a number of hops*

a If the packets have already traversed many hops and that the size of the packets are smaller than the packets that have just travelled a few hops, then reject these packets and accept the bigger packets
b If the packets are big and have survived many hops, accept these packets and reject those small packets that have just travelled few hops
c If the packets are big and traversed only a few hop, then also accept these packets and discard those that have traversed many hops
Discarding big packets in such scenarios may waste valuable resources, provided that the accepted packets are not corrupted and meet all the eligible criteria

of the forwarding node will update the TTL by deducting it after traversing each hop. The decision to discard the packets with low TTL at the very beginning is found to be a good ruling, apart from saving considerable resources for other transmissions.

- *Corrupted packets*. One of the causes for corrupted packets in WSN is the existence of bit error rate (BER). The higher the BER, the lossy the channel will be, and vice versa. Transmitting a big packet high in BER will create a high tendency for the data to be corrupted and thus dropped. On the other hand, transmitting small packets in high BER will reduce the chances of becoming corrupted, hence will generate high chances of survival through the network. Therefore the big packets should be dropped in high BER and small packets should be accepted for transmission. However, if the small packets are still corrupted for some reason, discard them to improve performance.

Figs. 4 and 5 show the proposed discarding method in different scenarios considering both 'before' and 'after' the hops traversing. For simplicity, these illustrations are made on the assumption of high expected lifetimes and with no duplicated packets which have been considered in the real analysis.

4 Multi-objective optimisation

Although SPD has been proven to have the ability to handle huge traffic convergence in congested areas [40, 41], it is still insufficient to just drop the packets without considering the best possible solution by means of optimisation. In other words, the selection of which packets are to be dropped could be further enhanced using the MOO: this may leave the results in the best possible state.

In the context of SPD, optimisation consists of either minimising or maximising certain OF within series of given constraints [42]. The final result should satisfy or meet all the defined constraints.

As the name suggests, MOO involves optimising two or more conflicting OF simultaneously. In other words, the MOO will find the best possible single solution that minimises or maximises these functions at the same time without any conflict. The proposed MOO is discussed in Section 5. All the parameters used are defined in Table 1, while performance metrics and the corresponding objectives that need to be optimised OF are shown in Table 2.

Table 1 Parameters and Definitions

Terms	Definitions
E	set of links
s	source or ingress nodes
t	destination or egress nodes
T	sets of destinations or egress nodes
(i, j)	link from node i to node j
F	the flow set
f	multicast flow
T_f	destination subset for the multicast flow f
X_{ij}^f	indicate whether the link (i, j) is used for flow f 1 = used; 0 = not used
C_{ij}	the available capacity of each link (i, j)
bw_f	bw for a flow f
α	link utilisation
r	weighted metric variable

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Table 2 Objective functions and constraints [42]

No	Performance metrics	Objective functions
1	No. of hops to traverse	$\sum_{f\in F}\sum_{(i,j)\in E} X_{ij}^{\mathrm{f}}$
2	End-to-end delay	$\sum_{f\in F}\sum_{(i,j)\in E} d_{ij}*X_{i,j}^{\mathrm{f}}$
3	Bw consumption	$\sum_{f\in F}\sum_{(i,j)\in E} \mathrm{bw_f}*X_{ij}^{f}$
4	Energy consumption	$\sum_{f\in F}\sum_{(i,j)\in E} \mathrm{En}_{ij}*X_{ij}^{\mathrm{f}}$
5	Packet loss rate	$\sum_{f\in F}\prod_{(i,j)\in E} \mathrm{plr}_{ij}*X_{ij}^{\mathrm{f}}$
6	Packet's lifetime (staleness)	$\sum_{f\in F}\sum_{(i,j)\in E} \mathrm{TTL}_{ij}*X_{ij}^{\mathrm{f}}$

4.1 Objective functions

OF are a set of parameters to be optimised by meeting the requirements of the pre-defined constraints. Here, we show how the OF in our proposed solution are derived. The functions to be optimised are given in (1), while the constraints are presented in (2)–(7). Here, we avoid the use of 'weighted sum' metrics because of difficulties in determining and assigning the values for the weight. It is also based on a single solution method and so needs several attempts to obtain the trade-off information [43].

Our first OF is concerned on the minimisation of the number of hops to be traversed by the packets. This can be presented by $\sum_{(i,j)\in E} X_{ij}^{\mathrm{f}}$ where ij is the link from node i to node j. However, several other concerns also need to be considered in achieving this objective. For instance, although we want to minimise the number of traversed hops, it might not be the best option as there might be a performance trade-off in other factors, such as the size of the packet, link delay and the energy consumption, which also play significant roles in determining the successful delivery of a packet and should thus be given serious consideration. Therefore the aim is to find the best possible solution that can satisfy all these factors.

The next OF is the total end-to-end delay of all the traversed hops. This can be calculated as $\sum_{(i,j)\in E} d_{ij}*X_{ij}^{\mathrm{f}}$ where $d_{i,\,j}$ represents the time taken to transmit the packets from node i to node j. This is also important as high end-to-end delay may jeopardise the overall performance. Where the number of hops to be traversed is low, but the delay for a selected link is high, the performance of the overall system will be affected. Thus, balancing these two factors is crucial to satisfy both criteria. We present the next OF as the summation of the minimum bw consumption $\sum_{(i,j)\in E} \mathrm{bw}_f*X_{ij}^{\mathrm{f}}$ from node i to node j. Similar to the delay, the bw consumption of the selected link should also be taken into account in order to optimise the overall performance. In this paper, the minimum bw consumption is desirable and preferable.

Since energy is the main concern in WSN, we also aim to minimise the energy consumption $\mathrm{En}_{ij}*X_{ij}^{\mathrm{f}}$. Our target is to achieve the minimum possible energy consumed in transmitting the packets. This has to be calculated for the total number of hops traversed. We also aim to reduce the probability of having packet loss. Therefore the following OF is defined: $\prod_{(i,j)\in E} \mathrm{plr}_{ij}$. This represents the loss rate at each visited node. In order to ensure the validity of packets until they reach the destination node, we have also derived the TTL of the packets given by $\sum_{(i,j)\in E} \mathrm{TTL}_{ij}*X_{ij}^{\mathrm{f}}$. This is in accordance with the concern to ensure the validity of the packets and thus ensure that they are not obsolete upon reaching their destinations.

4.2 Problem formulation

Given the above defined OFs, we formulate the problem. The objective is to choose the packets with maximum QoS by minimising the hops traversed, link delay, bw, energy consumption, packet loss rate and the TTL. These QoS are subject to maximum capacity of the link. All the defined OFs should meet certain pre-defined constraints, presented in the following equation

$$\begin{aligned}\text{Min } Z = &\left(r1*\sum_{f\in F}\sum_{(i,j)\in E} X_{ij}^{\mathrm{f}}\right)+\left(r2*\sum_{f\in F}\sum_{(i,j)\in E} d_{ij}*X_{ij}^{\mathrm{f}}\right)\\ &+\left(r3*\sum_{f\in F}\sum_{(i,j)\in E} \mathrm{bw}_f*X_{ij}^{\mathrm{f}}\right)\\ &+\left(r4*\sum_{f\in F}\sum_{(i,j)\in E} \mathrm{En}_{ij}*X_{ij}^{\mathrm{f}}\right)\\ &+\left(r5*\sum_{f\in F}\prod_{(i,j)\in E} \mathrm{plr}_{ij}*X_{ij}^{\mathrm{f}}\right)\\ &+\left(r6*\sum_{f\in F}\sum_{(i,j)\in E} \mathrm{TTL}_{ij}*X_{ij}^{\mathrm{f}}\right)\end{aligned} \tag{1}$$

Subject to

$$\text{Min } \alpha = \text{Max}\{\alpha_{i,j}\} \text{ where } \alpha = \frac{\sum_{f\in F} \mathrm{bw}_f*X_{ij}^{\mathrm{f}}}{C_{ij}} \tag{2}$$

In this case, α is the maximum link utilisation which should not be exceeded. Variable r_n represents the weight for each OF which are varied in the experiment and the total of r_n should be equivalent to 1. The summary of all the defined OFs are listed in Table 2.

Constraints: In achieving all the defined objectives, several constraints need to be satisfied. Equations (3)–(7) present our selected constraints. The first constraint identifies that for every flow f, only one path exists from the origin to destination node s. The flow that leaves the node should be positive, hence has the +1 sign. This flow is equivalent to 1 if the link is used: otherwise it should be set to 0. This can be presented as follows

$$\sum_{(i,j)\in E} X_{ij}^{\mathrm{f}} = 1;\ f\in F;\ i=s \tag{3}$$

On the other hand, the second constraint ensures that for every flow f, only one path can reach the destination node t. This implies that the flow that enters the other node is negative, hence has the –1 sign as shown in (4)

$$\sum_{(j,i)\in E} X_{ji}^{\mathrm{f}} = -1;\ i=t;\ f\in F \tag{4}$$

$$\sum_{(i,j)\in E} X_{ij}^{\mathrm{f}} - \sum_{(j,i)\in E} X_{ji}^{\mathrm{f}} = 0;\ f\in F; i\neq s; i\neq t \tag{5}$$

The third constraint presents the intermediate nodes involved in the transmission using the selected link from node i to node j. For every flow f, the summation between the intermediate nodes should be 0 since the exit link (+1) and the entry link (–1) are summed up together.

The fourth constraint reflects the characteristic of WSN where the required bw of the flow must be less than the available capacity C_{ij}. This is shown in the following equation

$$\sum_{f \in F} \sum_{(i,j) \in E} \mathrm{bw}_f * X_{ij}^{\mathrm{f}} \leq C_{ij}; \quad (i, j) \in E \tag{6}$$

Bandwidth is also the function of the number of hops traversed, and should be multiplied by the total number of visited nodes

$$X_{ij}^{\mathrm{f}_k} = \{0, 1\}, \quad 0 \leq r_i \leq 1, \sum_{i=1}^{6} r_i = 1 \tag{7}$$

On the other hand, (7) reflects that the range of r_n depends on the number of OF, which is 6 in our case.

5 Proposed multi-objective optimisation technique

In order to solve the pre-defined multi-objective QoS maximisation problems, we apply the *metaheuristic* approach that is based on the multi-objective evolutionary algorithm (MOEA). This section will show the computational solution to the previously stated problem. The definition of all the variables used in this technique is given in Table 3. The MOEA is one method used to address MOO and uses population approach in its search operations. This evolutionary optimisation (EO) includes more than one solution in every iteration and generates a new solution in each round. The selection of EO in solving MOO is a perfect choice [44] because of its simplicity, flexibility and wide coverage of applications.

MOO will normally result in several Pareto-optimal solutions which is defined as a set of trade-off optimal solutions, in which the improvement of one factor may degrade the performance of at least one of the other factors. Therefore it requires further processing to obtain a single desirable solution. The use of population in EO helps to automatically find the non-dominated solutions which represent performance trade-off among the pre-defined OF s in a single run. The unique concept of using a population approach (more than one solution) in each iteration can achieve a faster search besides providing a vast set of alternatives [45]. This is why it is really useful for solving the MOO problem.

The EO is made up of four main processes: 'selection, mutation, crossover and elite-preservation'. The initial process begins with selection procedures by creating some random solutions. The crossover operation is used to select two or more solutions (parents) randomly and create one or more solutions (child) by exchanging the information among the selected solutions. That means, in any iteration the population of an individual parent is combined and altered to obtain the child population. The resulting child solution is then rearranged in its region by mutation operation. Here, every variable is mutated using the probability of p_m. With that, one variable will be mutated per solution. EO will then perform a local search that is independent of the other solutions. The solution that satisfies all the design constraints will be considered as a feasible solution.

The solutions may produce trade-off or conflicts among the listed objectives. Therefore one optimal solution is crucially needed. This will sometimes requires compromising the other objectives. Therefore this final solution should be on the Pareto-optimal front. The solution will also be able to cover the entire range of the Pareto-optimal front solutions.

The schematic principle of MOO can be illustrated in Fig. 6. As shown, although there are many feasible non-dominated points, the MOO will choose only one solution using the higher-level information. Thus, the EO is very efficient in solving the MOO problems [44, 46].

The definition of the Pareto-optimal front can be given as follows.

Definition 1: We classify variable $x^* \in F \subset \Re^n$ as a Pareto-optimal solution if it is non-dominated with respect to F. Pareto-optimal set is defined as

$$P^* = \{x \in F | x \text{ is Pareto-optimal}\} \tag{8}$$

And Pareto front can be defined as follows

$$\mathrm{PF}^* = \{f(x) \in \Re^n \,|\, x \text{ in } P^*\} \tag{9}$$

where $\Re^n$ is nth-dimensional vector of the decision variables and $f(x)$ are the feasible criteria points. Therefore minimising each dimension of the criterion vector is often desirable (e.g. Minimal energy expenditure and lower end-to-end delay).

Table 3 MOEA variables

No	Variable	Meaning
1	x^*	potential Pareto-optimal points
2	p_m	probability or mutation
3	P^*	Pareto-optimal sets
4	F	frontier
5	PF*	Pareto front
6	$\Re^k$	n-dimensional vector of decision variable
7	$P_{\text{current}}t$	current set of Pareto-optimal solutions
8	$P_{\text{known}}t$	secondary population
9	$\mathrm{PF}_{\text{known}}t$	Pareto front of the secondary populations
10	u, f	OF
11	$P^{\text{restricted}}$	restricted Pareto front
12	$a_{ki,\,j}$	the ith entry of the decision alternative or action
13	α	credible level
14	$u(\bar{p})$	number of preferences between alternatives

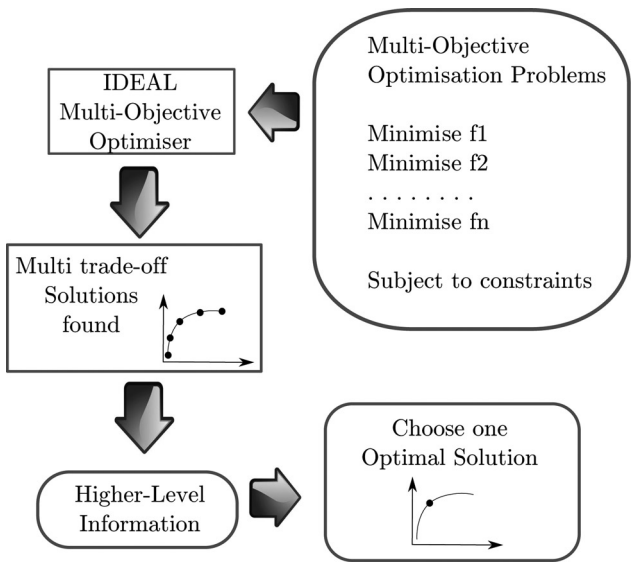

Fig. 6 *Architecture of the MOO algorithm*

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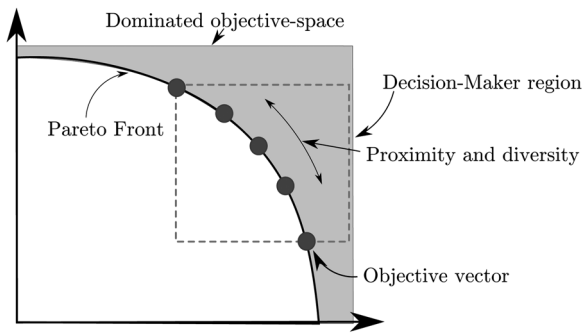

Fig. 7 *Pareto-optimal points and the decision region*

A clearer picture of Pareto-optimal points (black dots) is illustrated in Fig. 7, where the shaded area represents the dominated points. We also highlight the area where the decision about where the final optimal point is normally takes place.

Therefore we aim to find multiple different solutions (the so called Pareto-optimal solutions). There are, however, two concerns in solving this issue. First, how to generate the diversity into the population. The second question obviously concerns how to select the best possible solution based on the resulting sets of Optimal Pareto front. As the final results may have different sets of values, choosing the right final answer is normally challenging.

5.1 Mathematical derivation of the multi-objective evolutionary algorithm

At each iteration, a current set of Pareto-optimal solutions (P^*) is determined, and this is termed as $P_{\text{current}}(t)$ where t represents the generation number. Through a number of generations, the MOEA also generates a secondary population which is known as $P_{\text{known}}(t)$. The corresponding Pareto-optimal front for each of these sets is given by $\text{PF}_{\text{current}}(t)$, PF_{known} and PF*. By the end of the experiment, the following values should be satisfied

$$P_{\text{known}} = P^*;\ P_{\text{known}} \subset P^* \tag{10}$$

or

$$\{u_i \in \text{PF}_{\text{known}},\ \bar{u}_j \in \text{PF}^*{:}\forall i, \forall j\} \tag{11}$$

Here, we will only seek the solutions that are the most attractive to the decision- maker, in which the values u, f which represent the OF are close to 0. We are also interested in finding the credibility level α which is close to 1. Then the OF u of an individual $\bar{p}$ measures the amount of infeasibility and can be defined as follows

$$u(\bar{p}) = |\{(a_k, a_{kj}){:}\, a_{ki} S a_{kj}\}| \tag{12}$$

where $i = 1, 2, \ldots, m$, $i > j$ and $a_{ki} \in A = \{ a_1, a_2, \ldots, a_m\}$, $i = 1, 2, \ldots, m$. In this case, $[k_1, k_2, \ldots, k_m]$ is a permutation of $[1, 2, \ldots, m]$. As shown in the equation, a_{ki} outranks a_{kj}. The variable $\bar{p}$ is considered feasible when $u(\bar{p}) = 0$ and infeasible happens when $u(\bar{p}) > 0$.

Since not all the values found in Pareto front are of significant interest to our objectives, we wish only to find the restricted Pareto-optimal set which can then be defined as follows

$$P^{\text{restricted}} = \{\bar{p} \in P^*{:}\, ||(u(\bar{p}), f(\bar{p}))| \le \epsilon\} \tag{13}$$

where ε is a small, non-negative number. Then, the final set of Pareto-optimal points is $\text{PF}^{\text{restricted}}(t) = \{(P_1)^t, (P_2)^t, \ldots, (P_n)^t\}$. This represents the non-dominated set of solutions which is regarded as the final result.

6 Performance metrics

The performance of the proposed optimisation technique can be evaluated using the following defined metrics.

6.1 Energy consumption

As energy is limited in every sensor node, we aim to optimise the energy spent for each node so that the performance can be significantly improved. This ensures that the battery can last longer and the node can transmit more valuable packets. The loss of power or energy depletion will create very-low capability for the associated nodes to transmit the data especially in emergency situations. Therefore power depletion should be minimised to avoid serious performance degradation. This can be reflected in (1) which shows our objective in minimising energy consumption. This metric is measured in NS-2 which provides an energy model that allow us to measure the percentage of energy consumption for each node. This energy model divides the energy consumption separately between states; 'IDLE, SLEEP, transmission and received'. Here, it suffices to mention that we only consider the energy consumption for data transmission.

6.2 Throughput

Throughput is another important measurement to evaluate the performance of the proposed technique. The proposed optimisation scheme should be able to obtain high throughput while optimising and satisfying all defined OFs and constraints.

6.3 Packet delivery ratio (PDR)

The occurrence of packet loss in a sensor network is very critical as it might lead to other major consequences. Therefore we aim to minimise occurrences of packet loss using the proposed SPD-MOO and thus maximise the packet delivery ratio (PDR). Although this method can still result in some packet loss, the percentage is lower as some selected packets are dropped to minimise the amount of traffic. The lower the packet loss rate, the higher is the PDR and vice versa.

6.4 Time-to-live

The TTL is the average lifetime of a node that remains in order to transmit incoming packets. We define the TTL as TTL – (transmission delay/hop). The lower the TTL, the higher the chance of packets getting lost and not being forwarded to their destinations This is because, in such situations, nodes may have very-little energy to transmit the received packets or even the packets that it is generating. Lower TTL also does not guarantee that the packets could reach their destination in a timely manner and without errors. Hence, maximising the TTL is crucial. Using the

proposed approach, packets with very-low TTL will be discarded.

6.5 Average delay

Since applications in WSN mostly operate in real-time, it is crucial to minimise the average end-to-end delay to each destination in order to preserve high QoS. The average end-to-end delay in this paper can be expressed as follows

$$\text{Min}\frac{\text{Total\_Delay}}{\sum_{f\in F}|T_{\text{f}}|} = \text{Min}\frac{\sum_{f\in F}\sum_{(i,j)\in E} d_{ij}*X_{ij}^{\text{f}}}{\sum_{f\in F}|T_{\text{f}}|} \tag{14}$$

This function is directly related to the number of hops traversed. Since there are multiple paths to reach the sink nodes, we seek to obtain the smallest possible average delay. Note that a small number of hops does not translate into minimum average delay.

6.6 Blocking probability

Blocking probability (BP) is similar to packet loss rate. However, BP calculates the number of connections (flow f) that can actually be transmitted over the total number of flows requested for transmission (/*F*/). The formulation of BP is expressed in (15)

$$\begin{aligned} &\text{Min BP} = \frac{\text{Connection}_{\text{real}}}{\text{Connection}_{\text{total}}} \\ &\text{Max Connection}_{\text{real}} = \sum_{f\in F}\text{Max}(X_{ij}^{\text{f}})_{\lambda\in\Lambda,(i,j)\in,T\in T_{\text{f}}} \end{aligned} \tag{15}$$

Let $\text{Connection}_{\text{total}}$ be the total number of flows requesting transmission. The real number of connections that can actually be established is given by $\text{Connection}_{\text{real}}$. Thus, the BP can be expressed as $1 - BP$.

7 Experimental evaluation

In this section, we evaluate the performance of the proposed SPD-MOO technique based on the aforementioned performance metrics. For this purpose, simulation experiments have been conducted using NS-2. Packets discarding policy is handled by built-in 'Error Model via recv' protocol [37]. As an extension, the implementation of SPD is done using the 'select Error Model' that can be found in '/ns2/queue/errormodel.cc'. This built-in method in NS-2 is for general networking settings, so we have made some modifications to match the WSN scenario.

Performance comparisons with the standard WSN setup (STD-WSN) and the conventional PD technique of DT have also been provided. Here, the STD-WSN refers to WSN with the normal setting without the deployment of SPD-MOO. The STD-WSN consists of 10–100 sensor nodes which perform the sensing mission in a continuous manner and report the data to the cluster head (CH) which periodically conveys the data to the sink node. We assume that all the sensor nodes are homogeneous with the same capacity and capabilities. For compatible comparison with STD-WSN and the SPD-MOO, we have implemented the DT in WSN and it is sufficient to mention that the DTs referred to in this paper are based on WSN scenario. The performance is evaluated as shown in the next subsection, using the configuration setup in Table 4.

Table 4 Simulation setup

No	Input parameters	Setup
1	area of sensor field	1000 × 1000 m
2	number of sensor nodes	10–100
3	number of sink node	1
4	bandwidth	250 kbps
5	packet size	30–60 bytes
6	simulation time	1000 s
7	radio propagation model	two ray ground
8	antenna	omniantenna
9	frequency band	2.4 GHz
10	transmission range	50 m
11	energy model	battery

7.1 Packet discarding period

Fig. 8 gives a scenario when congestion is triggered which directly indicates the period in which the PD period is implemented. The three durations indicated by the arrows represent a massive number of packet arrivals above the defined threshold. In this situation, the occurrence of packet loss is inevitable and may trigger sudden fluctuations in the number of packets lost. Such a situation may require a robust technique to prevent and avoid further damage to the associated system. It is in this period that the proposed discarding policy is implemented in order to prioritise packets based on the aforementioned criteria and discard the less important packets. This method gives more ways to the other packets that carry more weight in the system. As a result, packet transmission rates are reduced, as well as the number of packets that have to compete for the limited resources.

7.2 Number of hops traversed against PDR

In order to measure the effectiveness of our SPD-MOO, we measure the effect of nodes's variation against PDR in various scenarios where the number of connecting nodes abruptly changed. As shown in Fig. 9*a*, the number of PDR decreases with the number of nodes. This accords with the theoretical concept where the increase in the total number of nodes automatically demonstrates the constant increase in the number of packets produced. Thus, as the available buffer is limited in sensor networks, there is strong competition among these packets to get through the network and some packets may be discarded.

Using the STD-WSN method resulted in a higher number of packets lost, as opposed to the number of accepted packets. A

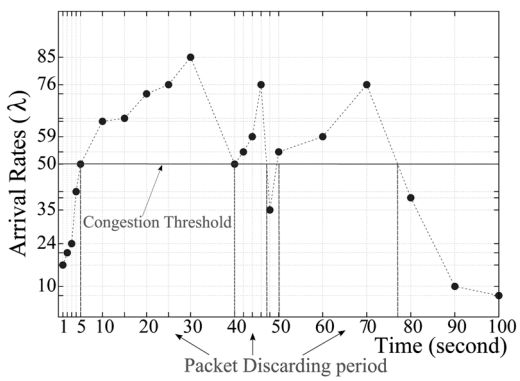

Fig. 8 *Discarding period which indicates the time in which packet losses are above certain pre-defined period*

It is within this period when the proposed PD method is being executed, shown by the arrows

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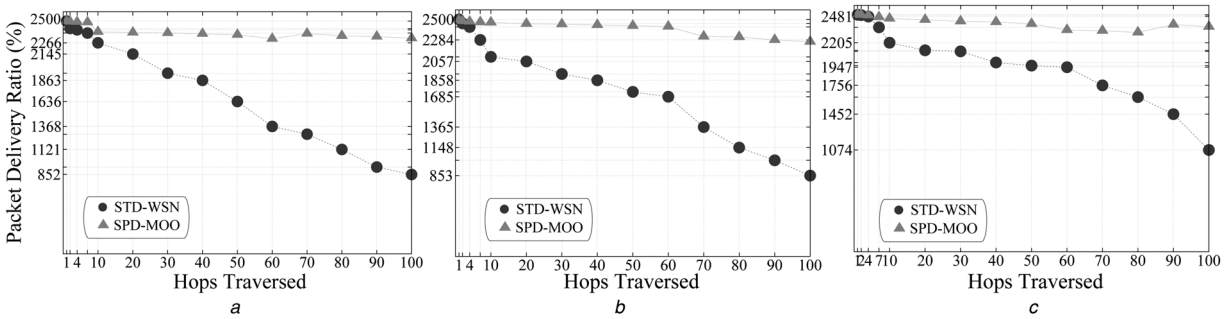

Fig. 9 *Effect on the number of competing nodes over the average number of packets accepted at destinations*

a Scenario 1
b Scenario 2
c Scenario 3

massive number of packets struggling to be accepted at the buffer may result in high collision rates and some packets need to be dropped. In contrast, the proposed STD-MOO gives a distinguished performance by the higher percentage of PDR. A similar pattern is observed in Figs. 9*b* and *c* using different scenarios. Therefore the proposed concept is proven effective with the high packet acceptance rate even in the massive number of nodes. This is because some unnecessary packets have been discarded in the early transmission, giving extra valuable space to handle the rest of the awaiting packets that deserve seamless transmission. This improvement has brought the increment to over 73% delivery ratio compared to the standard WSN without SPD-MOO.

7.3 Throughput against arrival rate

Throughput is among the important criteria used in measuring the effectiveness of the proposed SPD-MOO. For performance comparison, we segregate the received throughputs with DT and the STD-WSN. Fig. 10 shows the distribution of throughputs at the sink node, assuming that the arrival rate is 10 packets per second (pps). This is done with the deployment of 100 sensor nodes sending data simultaneously through some CHs and a sink node. Obviously presented in the figure, the STD-WSN protocol gives no increment in the throughput when packet arrival rates increase. Although the DT in WSN can slightly improve the performance, SPD-MOO handles the congestion well enough to achieve much better performance compared with the other two protocols as demonstrated in Figs. 10*a* to *c*.

Again, we presented three different outputs for result validation. However, in all the three cases the throughput started to slow when the packet arrival rate reached 400 pps. The throughput starts to demonstrate different shapes from the 400 pps onwards. These scenarios have distinguished the performance of the three studied protocols.

The performance of the selective discarding policy is dramatically improved since more buffer spaces are emptied during congestion in order to accept more awaiting packets, giving extra chances for these packets to be accepted.

7.4 Blocking probability against arrival rate

Fig. 11 shows that the packet arrival rate is directly proportional to the BP. The proposed SPD-MOO exhibits the best performance compared with the other two methods by giving the lowest BP. We firmly believe that this improvement is because of the early discarding method that has been proposed which reduces some amount of the unwanted packets and minimises the contention among the other packets. Therefore congestion is dramatically reduced. This explains the lowest BP achieved by the SPD-MOO as compared with DT and STD-WSN. On the other hand, DT achieves a slightly better performance than the STD-WSN since it employs the discarding policy once the buffer is full. BP is an important indication of the level of congestion in a network. A lower BP indicates fewer saturated links with smooth data transmission and a lower probability of having network congestion.

7.5 Percentage energy consumption

We also provide a comparison in the percentage energy consumption in Fig. 12*a*. Based on the observation, we can conclude that SPD-MOO is performing better than the other two mechanisms. This is because of the good characterisation of the discarding criteria. Although DT

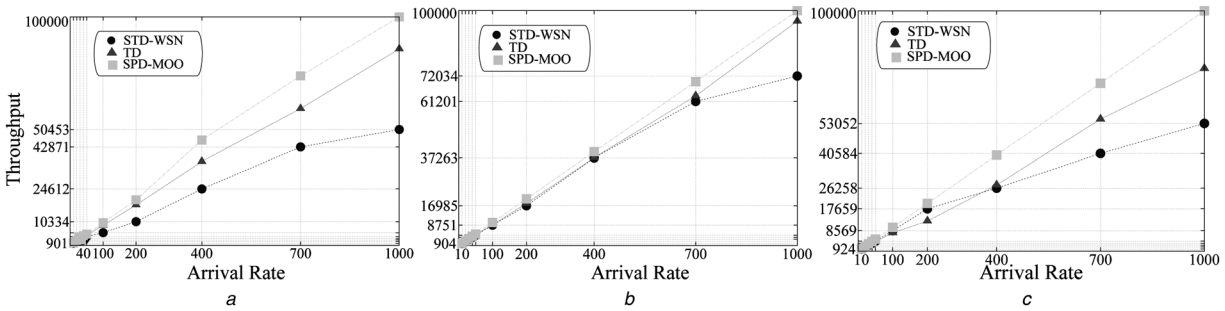

Fig. 10 *Performance studies of the resulting throughput with the variation of packets arrival rate*

a Scenario 1
b Scenario 2
c Scenario 3

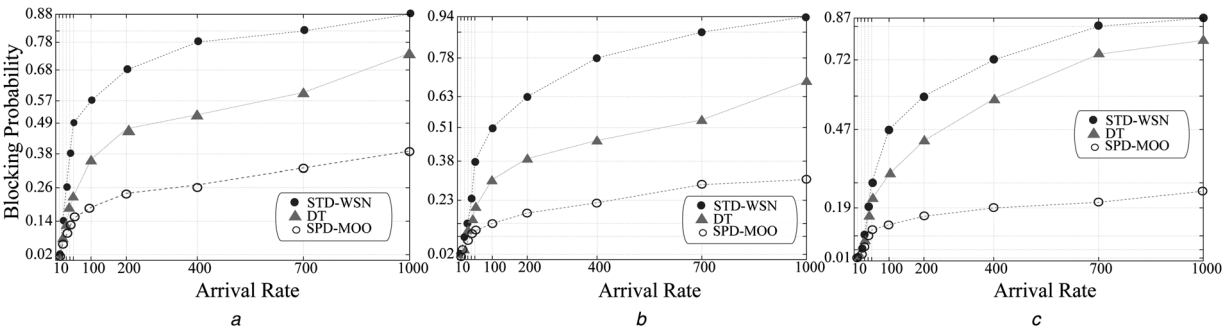

Fig. 11 *Comparison on the BP with the increase of packets arrival rate*

a Scenario 1
b Scenario 2
c Scenario 3

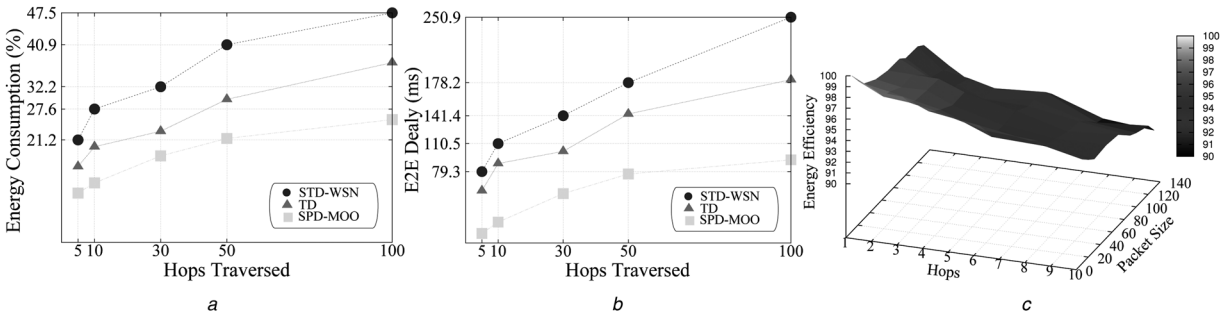

Fig. 12 *Performance comparison of*

a Energy consumption
b Average end-to-end delay
c Relationship between energy efficiency with the increase in the number of hops traversed and the size of the packets

achieves better performance than the STD-WSN, its performance still suffers high energy consumption since it has no characterisation on which packets to discard. This increases the average energy consumption.

Furthermore, the optimisation technique proposed in our method greatly helps to boost performance. On the other hand, the absence of the optimised discarding policy in STD-WSN has downgraded its performance.

7.6 End-to-end delay

Fig. 12*b* compares the performance in the resulting end-to-end delay. As shown, the delay in STD-WSN exceeds the real-time applications threshold value of 150 ms when the number of hops traversed increases to 100 nodes. A much better performance can be seen for DT because of the discarding policy during congestion to reduce the amount of traffic. Nonetheless, the resulting delay of the proposed SPD-MOO is far below the other two protocols. This reflects the adoption of the selective discarding policy and the optimisation approach which further enhance the whole performance.

7.7 Energy efficiency against number of hops and packet size

Fig. 12*c* shows the three-dimensional relationship between energy and the number of hops and packet size for the proposed SPD-MOO. Energy is efficiently spent when the packets are bigger and have to traverse only few hops as there will be fewer collisions. There is a slightly lower efficiency when the number of hops grows. However, the overall results obtained still exhibit a good performance even in heavy traffic conditions. This finding concludes that the proposed SPD-MOO is a robust technique in any traffic conditions.

8 Conclusions

This paper presents a SPD-MOO in solving congestion in WSN. The proposed solution is able to prevent congestion by discarding some unnecessary packets based on the optimisation criteria derived in MOO. Special MOO characteristics that simultaneously optimise multiple OF assists SPD to achieve better performance.

To the best of our knowledge, none of the solutions found have eliminated congestion from this perspective, making this mechanism a unique and novel approach. A mathematical model has been presented for the purpose of analysing the performance of the SPD-MOO. A comparison of the results is given to verify the accuracy of the model. The numerical results of several measurements proved the effectiveness of the proposed SPD-MOO technique.

Despite our focus within the domain of WSN, we believe that this method will work on other highly distributed systems. Our subsequent focus includes an investigation into the performance trade-off between fairness and energy consumption, an issue of paramount importance for WSN. Additionally, we intend to adapt this proposed technique for use in other distributed networking domains.

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