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Investigation of Data Dissemination in Wireless Sensor Network Using an Instantly Decodeable Network Coding

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ABSTRACT: Wireless Sensor Networks (WSNs) are networks of small, cheap, independent battery-powered sensor nodes, which finds applications in agriculture, health care, intrusion detection, asset tracking, habitat monitoring and in many other fields.It is sometimes necessary to disseminate data via wireless links after the deployment of sensors so as achieve the objectives of sensors configurations parameters adjustment or distribution of commands management and queries to sensors. In this research, we will consider how Shortest Path Minded Sensor Protocols for Information via Negotiation (**S**PIN)-Recursive (SPMS-Rec), which reduces the energy dissipated in the event of failures by requiring intermediate relay nodes to try alternate routes, is suitable for data dissemination. Owing to the power constraints and memory limitations of sensor nodes, 'Instantly Decodable Network coding' (IDNC) will be considered because of its practicality, relevance and numerous desirable properties such as instant packet recovery, simple XOR-based packet encoding and decoding, and zero buffer memory to store un-decoded packets.

Keywords: Wireless Sensor Networks, Sensor node, Sink, Data dissemination, instantly decodable network coding.

I. INTRODUCTION

Wireless Sensor Networks (WSNs) are networks of small, cheap, spatially distributed autonomous independent battery-powered sensor nodes. These nodes consist of a microcontroller and a radio for communication, as well as one or more sensors. networks (WSNs) comprise of many collaborating sensor nodes capable of sensing, computing and communicating sensed signals to a remotely located server. They are used to monitor physical phenomena such as pressure, sound, heat, air pollution, health status, and so on, in the environment of the sensor nodes. The sensed data is transmitted to base station by cooperative capabilities of the sensor nodes. Figure 1 shows a functional block diagram of wireless sensor node. A typical sensor node consists of the following components: sensing subsystem including one or more sensors incorporating a transducer and analog-to-digital converters) for data acquisition, processing subsystem including a microcontroller and memory for local data processing, radio subsystem for wireless data communication, and power supply and storage unit. In addition, sensor nodes may also include components such as a location finding unit to determine their position, a mobilizer to change their location or configuration (e.g., antenna's orientation), and so on.

WSN may contains several thousands of nodes capable of communicating with other nodes using radio signals. Meanwhile, nodes have limited resources such as computation speed, memory capacity, battery power, bandwidth, etc. In actual deployment computation speed may be traded off for battery power. Moreover, nodes should be capable of self-organization into a network infrastructure, with information retrievable via queries retrieved from the base station. Self-organization will allow for turned ON nodes to form a network and setup routes with no external intervention.

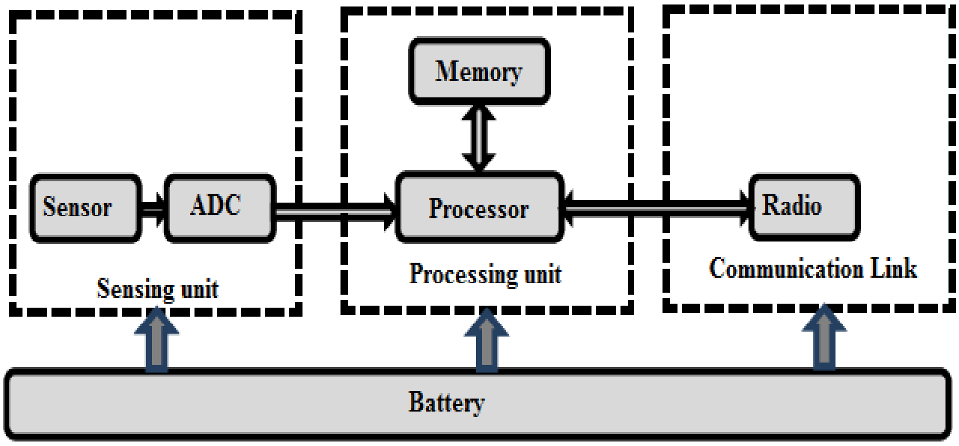

Figure 1: Block diagram of wireless sensor node

When deployed in large numbers, sensor nodes offers a fine monitoring capability, which can find useful applications in agriculture (de la Concepcion, Stefanelli, & Trinchero, 2014), intrusion detection, asset(s) tracking, as well as in many other fields of human endeavours (Brunelli & Rossi, 2014; Butun, Morgera, & Sankar, 2014; Durisic, Tafa, Dimic, & Milutinovic, 2012; Jelicic, Magno, Brunelli, Paci, & Benini, 2013; Prabhu et al., 2014). One major component used in this network of sensors is a special technical component that helps to monitor the sensor's health and the health of neighbouring sensors. Although the health messages are not too critical to the correct applications execution, their use is viewed more as preventive maintenance. Health messages are usually seldom sent or sent rather infrequently (about once per hour or less dependent on the duty cycle) with no guarantee on their delivery (Akkaya, Younis, & Youssef, 2007; Jiang et al., 2015).

Wireless Sensor Networks (WSN) is intended for monitoring the physical or environmental conditions. The chief requirement of a wireless sensor node is to sense and collect data from a certain domain, process it and transmit it to the sink where the application is localized. However, if the direct communication between a sensor and the sink is left uncontrolled or untamed, this may force nodes to emit their messages with such a high power that their resources could become quickly depleted. Hence, the collaboration of nodes to ensure that distant nodes communicate with the sink becomes a critical requirement. This understanding underscores the need for the incorporation of intermediate node or nodes which help to propagate messages thus making sure that a route with multiple links or hops to the sink is established.

Taking into cognizance the reduced capabilities of sensors, the communications with the sink could be initially conceived without a routing protocol. With this premise, the flooding algorithm stands out as the simplest solution. In this algorithm, the transmitter broadcasts the data, which are consecutively retransmitted via several intermediate nodes in order to ensure their arrival at the intended destination. However, its simplicity brings about significant drawbacks. Firstly, an implosion (which is a violent inward collapse of a structure or system due to pressure imbalance) is detected because nodes redundantly receive multiple copies of the same data message. Additionally, these anomalies may be detected by several nodes in the affected area, therefore, multiple data messages containing similar information are introduced into the network. Moreover, these irregularities gain further momentum when we consider the fact that the nodes do not take into account their resources to limit their functionalities.

One optimization relies on the gossiping algorithm. Gossiping algorithms helps to avoids implosion as the sensor transmits the message to a selected neighbour instead of broadcasting to all its neighbours as in the classical flooding algorithm. However, overlap and resource blindness are still not eliminated. Furthermore, these inconveniences are further highlighted as the number of nodes in the network increases. Due to the deficiencies and loopholes of the previous strategies, routing protocols become necessary in wireless sensor networks.

One of the major limitations is in the nodes identification. Since wireless sensor networks are of potentially unique identifier such as the MAC (Medium Access Control) **address** or the GPS **coordinates** is not recommended as it forces a significant payload in the messages. However, this drawback is easily overcome in wireless sensor networks since an IP address is not a requirement to identifying the destination node of a specific packet. In fact, attribute-based addressing fits better with the specificities of wireless sensor networks. In this case, an attribute such as node location and sensor type is used to identify the final destination. Once nodes are identified, routing protocols are in charge of constructing and maintaining routes between distant nodes. The varieties of ways in which routing protocols operate make them appropriate for certain applications.

The inclusion of a routing protocol in a wireless sensor network constitutes a very arduous task. One of the major limitations is in the nodes identification. Since wireless sensor networks are of potentially unique identifier such as the MAC (Medium Access Control) **address** or the GPS **coordinates** is not recommended as it forces a significant payload in the messages. The aim of this research proposal is to investigate data dissemination in wireless sensor network using an instantly decodable network coding

1.1. Design Constraints for Routing in Wireless Sensor Networks

One of the main design goals of WSNs is to carry out data communication while trying to prolong the lifetime of the network and prevent connectivity degradation by employing aggressive energy management techniques. Due to the reduced computing, radio and battery resources of sensors and limited bandwidth of the wireless links connecting sensor nodes, routing protocols in wireless sensor networks are expected to fulfil the following requirements:

Autonomy: The assumption of a dedicated unit that ensures that the radio and routing resources do not stand in the way of wireless sensor networks as it could be an easy point of attack. Since there will not be any centralized entity to make the routing decision, the routing procedures are transferred to the network nodes.

Energy Efficiency: Routing protocols should prolong network lifetime while maintaining a good quality of connectivity in order to ensure the communication between nodes. It is important to note that the routine battery replacement in the sensors is not feasible since most of the sensors are randomly placed. Added to that is a consideration of the fact that some devices are buried to make them able to sense the soil.

Scalability: Wireless sensor networks are composed of hundreds of nodes so routing protocols should function and work with this amount of nodes.

Resilience: No mechanical or electrical device or devices are perfect, as such even sensors may unpredictably stop operating due to environmental reasons or due to overwhelming power consumption from the battery. Hence, routing protocols should be able to cope with this eventuality such that when a current-in-use node fails, an alternative route could be discovered to complete the task of data dissemination.

Device Heterogeneity: Although most of the civil applications of wireless sensor network rely on homogenous nodes (use of the same type of sensors), the introduction of different kinds of sensors could report significant benefits. The use of nodes with different processors, transceivers, power units or sensing components may undoubtedly improve the characteristics of the network. Among others, the scalability of the network, the energy drainage or the bandwidth all benefit from the nodes heterogeneity.

Mobility Adaptability: The different applications of wireless sensor networks could demand that each node copes with its own mobility, the mobility of the sink or the mobility of the event to sense. Routing protocols should provide appropriate supports for these movements. This is not to say that the routing protocols are shielded from all challenges that beset all other protocols. Consider for instance other significant routing challenges and design issues that affect even the routing processes in WSNs, these are: Node deployment, Energy consumption without losing accuracy, Data reporting method, Fault tolerance, Network dynamics, Transmission media, Connectivity, Coverage, Data aggregation, Quality of service.

An alternative approach to prolonging network lifetime while preserving network connectivity is to deploy a small number of costly, but more powerful, relay nodes whose main task is to communicate or handshake with other sensors or relay nodes.

WSN nodes are typically organized in one of three types of network topologies. The three possible topologies in common use are: Star topology, where 'each node connects directly to a gateway' or Cluster tree network topology, where 'each node connects to a node higher in the tree and then to the gateway, this connection ensures that data is routed from the lowest node on the tree to the gateway'. Finally, to offer increased reliability, the third type of nodes organization i.e. the Mesh networks topology features nodes that are capable of connecting to multiple nodes in the system and transmit data through the most reliable path available at any instant of time.

1.2. Data dissemination protocol

As sensor networks are increasingly getting used in various applications which require collection and analysis of data. Data dissemination is an important part of any sensor network. Our starting point is a recently proposed SPIN-based protocol, called Shortest-Path Minded SPIN (SPMS), in which meta-data negotiations take place prior to data exchange in order to minimize the number of data transmissions. We propose a redesign of SPMS, called SPMS-Rec (SPMS-Recursive), which reduces the energy expended in the event of failures by requiring intermediate relay nodes to try alternate routes.

The instantly (instantaneously) decodable network coding (IDNC) is attractive owing to the following obvious merits:

1) It allows for fast decoding of packets at the receivers end, a property that is significant and of great importance to applications requiring progressively refined input, without long delays.

2) It allows for a simple XOR decoding at the receivers, thus eliminating the need for computationally expensive matrix inversions at the receivers.

3) It does not require any buffer(s) for the storage of non-instantly decodable packets for future decoding possibilities.

II. LITERATURE REVIEW

In generally, data dissemination in WSNs must meet two requirements. Firstly, it should be reliable despite of the unreliable wireless links in the network. Secondly, it should be time-energy-efficient to cover the entire network(Zheng et al. 2016). Large number of transmissions and long dissemination time mean sustained interruptions in the normal network operations, which is not advisable. It is therefore significant to reduce the transmissions and dissemination time. However, data dissemination in a WSN suffers from challenges, which may deteriorate the reliability andefficiency.

In recent years, many data dissemination strategies and protocolshave been presented in literatures to deal with these challenges above. These approaches can be divided into twocategories: Non-coding-based (Hamida & Chelius 2008; Zheng et al. 2015; Park et al. 2010; Wang et al. 2010; Park et al. 2011; Mo et al. 2013; Gao et al. 2013; Xie, et al. 2014; He et al. 2015; Zhao et al. 2015; Antonopoulos & Verikoukis 2014)and coding-based approaches(Antonopoulos & Verikoukis 2012; Antonopoulos et al. 2014; Rossi et al. 2008; Hagedorn et al. 2008; Dong et al. 2011; Koetter & Medard 2003; Wang & Li 2006; Xiao et al. 2009; Sun et al. 2013; Sorour &Valaee 2013; Liu & Sung2014; Yu et al. 2014; Sorour et al. 2014; Aboutorab & Sadeghi2016; Muhammad et al. 2013; Wang et al. 2013). The performance of non-coding-based approaches degrades seriously with unreliable links (Gao et al. 2013). This is because when the link quality becomes poor, the retransmissions grow dramatically, which further makes the data packets easy to be collided. Consequently, decreasing the number of retransmissions while keeping integrity of data bulk is very important to data dissemination. Coding-based approaches employ network coding to encode the original packets into coded packets at BS. Upon the receivers obtain enough coded packets, theywill decode the original packets successfully. Random linear network coding (RLNC) has been firstly proposed to put this approach into practice in data dissemination in (Koetter & Medard 2003). RLNC can achieve the best throughput in this application. However, the receivers cannot decode any packet before enough linearly independent packets have been received, thus resulting in poor delay performance of RLNC. Inaddition, one practical issue of RLNC is its high complexity as the decoding process involves Gaussian elimination, which is of high computational overhead. It can severely degrade end device performance (Wang & Li 2006).As a result, applying RLNC in data dissemination in WSNs is not very feasible for the limited computation and storage capability, which may constrain the performance improvement.

In order to reduce the decoding complexity and delay, a simpler strategy based on exclusive or (XOR) operation has been proposed. In this strategy, the sender combines different “wanted” packets from different receivers so that one retransmissioncan serve more receivers compared with the simple Automatic Repeat Request (ARQ) and Hybrid Automatic Repeat Request (HARQ) protocols. This strategy is primarily used in the wireless multicast/broadcast systems to reduce the number of retransmissions. Xiao et al. (2009) developed an approach called Network Coding Wireless Broadcasting Retransmission (NCWBR) which effectively reduces the average number

of transmissions. Later, a modified approach improved network coding broadcasting retransmission (INCBR) has been proposed bySunet al. (2013) to improve transmission efficiency while reduce complexity. This strategy has been called as instantly decodable network coding (IDNC) recently for the decoding of an original packet can be achieved once an instantly decodable

coded packet is received successfully (Sorour & Valaee 2013; Liu & Sung 2014; Yu et al. 2014; Sorour et al. 2014). Otherwise, instant decoding releases the requirement of large storage at receivers, which is used to buffer received coded packets in RLNC scheme. These simple decoding and no-buffer properties allow design of cost-efficient receivers and is very preferable to the sensors in WSNs. Recently, IDNC has been universally used in several fields such as lossy feedback conditions (Sorour et al. 2014), cooperative data exchange (Aboutorab & Sadeghi 2016), unequal error protection (Muhammad et al. 2013) and in-order progressive retransmission (Wang et al. 2013).

Likewise,study of applying IDNC in data dissemination of WSNshas been done to achieve energy efficiency by Wang et al. 2010based on a maximum weight clique (MWC) model. However, the complexity of MWC scheme rises rapidly with increase of the number of packets, receivers and packet erasure ratio (PER). Hence, it is not suitable to be used in the large-scale networks, such as the WSNs with hundreds or thousands of sensors.

III. MATERIALS AND METHOD

In this chapter, models and architecture for data dissemination for the WSNs are described. Also described are relevant mathematical expressions needed.

3.2. System Architecture and Model

3.2.1. Cluster-Tree based System Architecture

We assume that each sensor has an omnidirectional antenna and the same transmitting power in a WSN. And the sensors also share the same communication channel (e.g., same frequency band, same spreading code or frequency hop pattern). The medium access scheme can be random or reservation based. We assume bidirectional and halfduplex links.

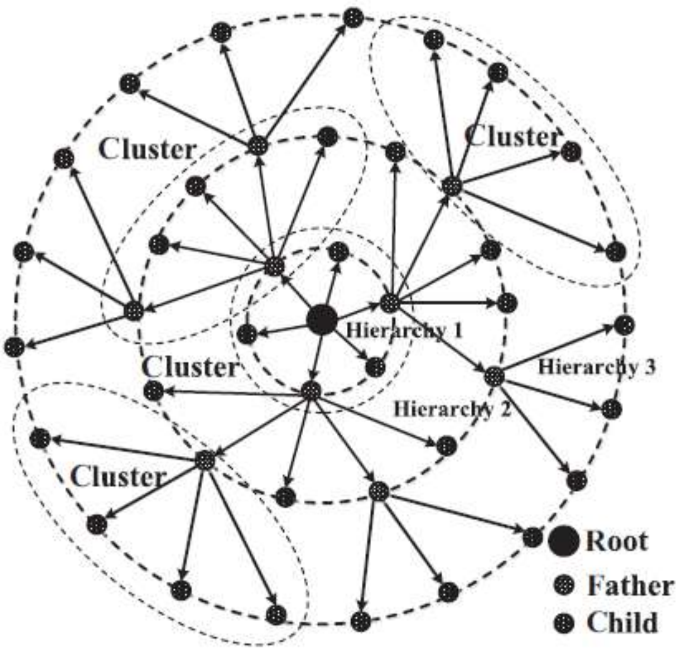

Figure 2: Cluster-tree based system architecture of WSNs.

We also assume a connected network, i.e., no partition exists in the network. If partitions do exist, our approach will create a backbone on each separate subnetwork independently. Cluster-tree based networkmodel is a classical network topology that can perfectly represent characteristics of WSNs, while BS and all sensors in the network are divided into different hierarchies and groups which are called as clusters as shown in Figure 2. All nodes in WSN can be clarified into three categories. 1) Root, the BS or data source in the process of data dissemination. 2) Father, a sensor that is elected to act as relay, which can forward data to his children or other nodes. Root is a special node for it also acts as the father of the nodes in the first hierarchy. 3) Child, the node that receives data from its father. In addition, all the nodes except the root are placed into different hierarchies according to the minimum number of hops from root. In the illustrated scenario of Figure 3.1, three hierarchies are presented. In this architecture, one node may be father for it relaying data to the nodes in its next hierarchy and may be a child receiving data from a node in its previous hierarchy as well. A father and all its children constitute a cluster in which father is responsible for disseminating data to its children. In this research, we assume that the root and all fathers are capable of IDNC encoding and all children are capable of IDNC decoding correspondingly. For the upstreams in our cluster-tree architecture, data collected by each sensor is delivered to the root along the constructed tree hop-by-hop. Father also act as the relays to realize the “many-to-one” traffic pattern. However, this traffic pattern may result in quick energy consumption at fathers and unbalance of lifetime in the whole network. Hence, replacement of fathers or relays and deploying more nodes as relays are important toWSNs. In this sense, how to balance energy consumption to extend the network lifetime while still keeping good energy efficiency is still an open issue. This researches focuses on the data dissemination of downstreams. The data generated by root will be disseminated from elected fathers to their children hierarchy by hierarchy until all intended sensors have received the data bulk successfully. If a father can deliver the data to their children more reliable and efficient, i.e., the number transmissions and complexity are reduced, energy-saving will be achieved and the lifetime of the network will be extended. Hence, how to reduce the number of transmissions for the data dissemination in a cluster with low complexity is a vital problem.

3.2.2. Cluster Partition and Father Election

By intuition, the reliability is improved with increase of the number of clusters in that the farthest distance between a father and his children is shortened and PERs are proportional to the physical distance in WSNs generally. However, more clusters imply that more sensors will act as fathers and unnecessary energy will be consumed at them to deliver data. Therefore, optimized number of clusters and cluster partition should be given to achieve good trade-off between delivery reliability and energy efficiency. In addition, fathers are responsible for relaying data to their children. The energy consumption of fathers is much more than other nodes’. The elected fathers have to store enough energy to complete the data dissemination and other missions. However, too many children and bad link status may result in more retransmissions. Hence, several factors should be considered into the father election, such as residual energy, degree of connectivity (number of connected sensors in the next hierarchy), linkstatus information.

In this research,our emphasis is placed on the IDNC data dissemination in a cluster. Thus, the process of cluster partition and father election is presented briefly as the following steps.

Step 1. Hierarchy division: Root floods global broadcast message (GBM) periodically to all sensors hop by hop. A sensor receives this message and feeds back its ID, its previous hop sensors’ IDs and the minimum number of hops (MH) from root to it. Root divides all sensors into different hierarchies according MHs.

Step 2. Father election: After step 1, fathers in each hierarchy will be elected to relay data to the next hierarchy. If the number of sensors in Hierarchy i is NSi, the number of elected fathers NFi in this hierarchy will be set to around √NSi. In this step, besides the factors presented above are important to the election, another thing needed to be considered is that all the sensors inthe next hierarchy must be covered by elected fathers.

Step 3. Cluster partition: All sensors will be partitioned into different clusters by root according to feedback of GBM. However, some sensors may be covered by multiple fathers. In this case, these sensors should join in the cluster that the link status is the best preconditioned by the number of children in this cluster is not over the threshold δ_c. Here δ_c, is the maximum degree of connectivity presented for fathers to ensure transmission efficiency.It is because that the transmission efficiency deteriorates with increase of the number of children in a cluster.

3.2.3. IDNC Data Dissemination Model

To improve the efficiency of data dissemination in a cluster, the IDNC data dissemination model will be established. The network model is actually a general broadcast model in wireless networks. This model contains a sender (root or father, we call them as father uniformly in the following) which is denoted as S for delivering a generation of original data packets to a set of M receivers (children) denoted as R = $\{R_1, R_2, \cdots, R_M\}$. A generation consists of a set of N packets denoted as P = $\{P_1, P_2, \cdots, P_N\}$. **Data dissemination process**is divided into two phases: The initial transmission phase and retransmission phase. In the initial transmission phase, father sequentially broadcasts all the original packets of the generation. These transmissions subject to link loss, fading, interference and sleep of sensors so that some packets may be erased. For each packet that received successfully by a child, acknowledgement (ACK) will be fed back to father. The father stores ACK information and the status feed matrix (SFM) will be formed when the initial phase comes to the end.

Definition 1: SFM is defined as a list in which the collected status information of each original packet for each child is represented. This list is a M × N matrix, whose row coefficients represent the children and column coefficients represent original packets. SFM is a '0,1' matrix. Elements in SFM is denoted by $w_{i,j}$ (i = 1, 2, ・・・,M; j = 1, 2, ・・・,N). If $w_{i,j}$ = 1, it is denoted that R_i has not received or decoded $P_j$successfully. Else if $w_{i,j}$ = 0, it is denoted that $P_j$has already been in the buffer of R_i. Afterwards, the retransmission phase begins to recover erased packets with IDNC packets. Here, each IDNC packet is able to serve children that miss different original packets simultaneously in each round of retransmission. The target of retransmission is disseminating a generation with minimum number of transmissions so that the energy-efficiency achieves at father. In retransmission phase, the transmissions may still subject to link loss, fading, interference and node sleep. Hence, every child should feedback ACK information yet to be used to update SFM at father for subsequent delivery. In order to analyse and simulate the performance of our proposed approach, we give some assumptions as follows,

Assumption 1: After the initial transmission phase, father can estimate the link status for every child through signal-to-noise ratio of received ACK signal.

Assumption 2: The size of ACK/negative acknowledgement (NACK) packets is much smaller than the data packets and the stronger protection, which can be achieved by high transmitting power, low order modulation and low coding rate usually employed for control packets as shown by Sorour & Valaee (2013). Without loss of generality, we assume that the ACKs and NACKs are fed back to father without missing.

Assumption 3: In WSNs, the existence of path loss, wireless interference, collision, signal fading and shadowing makes the scheduling of data packet transmissions a challenging problem that needs to be carefully addressed to achieve effective and efficient accesses to the wireless medium. The cross-layer design that considers the MAC, network and transport layers together has been proposed to achieve different goals and the corresponding schemes has been summarized byWang & Liu (2011), and the importance and the impact of physical layer to upper layers has been presented by Antonopoulos et al. (2013). This paper will not concern this topic and we assume that links among father and children are independent with each other through good cross-layer handling.

Table 1: An example of WSFM

Children	Original packets							
	P_1	P_2	P_3	P_4	P_5	P_6	P_7	P_8
R_1	0.90	0.90	0.00	0.00	0.90	0.00	0.00	0.00
R_2	0.00	0.00	0.80	0.00	0.00	0.80	0.00	0.00
R_3	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.70
R_4	0.85	0.00	0.00	0.00	0.00	0.00	0.85	0.00
R_5	0.00	0.80	0.80	0.00	0.00	0.80	0.00	0.00
R_6	0.75	0.00	0.00	0.00	0.00	0.75	0.00	0.00

Table 2: An example of status feed matrix

Children	Original packets							
	P_1	P_2	P_3	P_4	P_5	P_6	P_7	P_8
R_1	1.00	1.00	0.00	0.00	1.00	0.00	0.00	0.00
R_2	0.00	0.00	1.00	0.00	0.00	1.00	0.00	0.00
R_3	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00
R_4	1.00	0.00	0.00	0.00	0.00	0.00	1.00	0.00
R_5	0.00	1.00	1.00	0.00	0.00	1.00	0.00	0.00
R_6	1.00	0.00	0.00	0.00	0.00	1.00	0.00	0.00

Assumption 4: As the assumptions bySorour & Valaee (2013) and Sorour et al.(2014), we also assume PER between father and any child keeps constant during the transmission of a generation. For R_i, we assume that PER is pi that is determined by the link status and sleep probability.
Definition 2: WSFM is defined as a list in which both the packet status information and PER information for each child are represented. This list is also a M × N matrix whose elements are expressed by $\tilde{w}_{i,j}$ (0 ≤ ˆ $\tilde{w}_{i,j}$ < 1; i = 1, 2, ・・・,M; j =1, 2, ・・・,N). If R_i has not received or decoded $P_j$successfully, $\tilde{w}_{i,j}$ = 1 − pi> 0. It gives the success probability to deliver a packet from father S to R_i. Otherwise, $\tilde{w}_{i,j}$ = 0. Table 1 gives an example of WSFM that has six children and eight original packets.

$$\sum_{v=1}^{K} w_{i,k_v} = 1 \quad (1 \le k_1 \le \cdots \le k_K \le N) \tag{1}$$

Theorem 1: If R_i is able to decode an original packet from IDNC packet $P_c^k : P_c^k$ = P_{k1}⊕P_{k2}⊕・・・⊕P_{kK}(1 ≤ k_1≤ ・・・ ≤ k_K≤ N) that is encoded and disseminated by father in the k-th retransmission, i.e., instantly decodable to R_i, WSFM must fulfill condition as follows:

$$\sum_{v=1}^{K} \lceil \hat{w}_{i,k_v} \rceil = 1 \quad (1 \le k_1 \le \cdots \le k_K \le N) \tag{2}$$

Proof: For child R_i and IDNC packet P_c^k , if all elementsin {$\hat{w}_{i,k_v}$ (v = 1, 2, ・・・,K)} are '0', it means that all originalpackets that participate in IDNC operation in the kth retransmissionhave already been received successfully by R_i. Hence,there is no gain to R_i in this transmission. Furthermore, if twoor more than two original packets wanted by R_i participate inIDNC operation, it will not be able to decode any original packetsthrough XOR decoding. Hence, only one of these scheduledpackets is not in the memory, i.e., only one element in{⌈$\hat{w}_{i,k_v}$⌉(v = 1, 2, ・・・,K)} is '1' and the others are '0', R_i will be able to decode this original packet after the IDNC packethas been successfully received. Thus, we obtain equation 1.We will give an example of Theorem 1 based on Table 1. IfP1, P2 and P5 has been selected as the coded packets at the kthretransmission, i.e., P_c^k = P1 ⊕P2 ⊕P5, R1 will not be ableto decode any source packet from P_c^k for all the three codedpackets are not in the

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buffer of it and XOR decoding will not be valid. Upon the packet status of R_1denoted in Table 3.1, (3.1) is equal to $\lceil \hat{w}_{1,1} \rceil + \lceil \hat{w}_{1,2} \rceil + \lceil \hat{w}_{1,5} \rceil$ = ⌈0.9⌉+ ⌈0.9⌉+ ⌈0.9⌉=1 + 1 + 1 = 3. In the similar case, R_3 cannot benefit from Pkcfor all the three coded packet has already been in the buffer of it and (1) for R_3 is 0 + 0 + 0 = 0, which is not equal to 1 as well. However,R_4 has received P2 and P5successfully and only P1 is not in its buffer. Therefore, R_4can decode a source with XOR operation (P1 ⊕P2 ⊕P5) ⊕P2 ⊕P5 = P1. Equation (1) at R_4 is ⌈0.85⌉+ 0 + 0 = 1 + 0 + 0 = 1.

Actually, $\lceil \hat{w}_{i,j} \rceil = w_{i,j}$. In other words, if $\hat{w}_{i,j} > 0$, $w_{i,j}$ = 1. Therefore, WSFM can be transformed to SFM by replace $\hat{w}_{i,j}$ (∀i = 1, 2, · · · ,M; ∀j = 1, 2, · · · ,N) with ⌈$\hat{w}_{i,j}$⌉. We give an example of SFM in Table 2, which is transformed from Table 1. Likewise, WSFM can be obtained by assigning $\hat{w}_{i,j}$ with $w_{i,j}$ ×(1−pi). And Theorem 1 can be also presented with SFM as follows: If $R_i$wants to decode an original packet from P_c^k , i.e., instantly decodable to R_i, SFM must fulfill condition

Definition 3: Transmission gain G_i^k is defined as the probabilitythat Ri decodes an original packet in the kth round ofretransmission after IDNC packet P_c^k is transmitted. G_i^k is expressed as the following equation (3):

$$G_i^k = \begin{cases} \sum_{v=1}^{K} \hat{w}_{i,k_v} (1 \le k_1 \le \cdots \le k_K \le N), \\ 0, \end{cases} \tag{3}$$

Definition 4: Total transmission gain (TTG) G^k is defined as the expected number of children that can recover an original packet in the kth retransmission with IDNC packets P_c^k being disseminated by father. This expectation can be denoted as follows:

$$G^k = \sum_{i=1}^{M} G_i^k. \tag{4}$$

Using IDNC packets, the number of retransmissions in the second phase can be reduced significantly. Generally, the larger TTG implies that the more children can benefit from a round of IDNC retransmission. However, different original packets are selected to be encoded into an IDNC packet bring different TTGs. Considering Table 1 as an example, father selects P1 and P3 to be encoded into P1 ⊕P3 through XOR operation. Assuming that the link status is ideal and all children are active, this IDNC packet will be received by them, and R_1, R_2, R_4, R_5, R_6 will recover an original packet with XOR decoding. In the real environment, this IDNC packet is received successfully by R_1, R_2, R_4, R_5, and $R_6$with probability 0.9, 0.8, 0.85, 0.8 and 0.75 respectively. The expected number of children that can decode an original packet successfully is 0.9 × 1 + 0.8 × 2 + 0.85 × 1 + 0.75 × 1 = 4.1, i.e., TTG is 4.1. Otherwise, if the IDNC packet is P1 ⊕P6,⌈$\hat{w}_{6,1}$⌉+⌈$\hat{w}_{6,6}$⌉= 2 and equation (1) will not fulfilled for R_6. Hence, R_6 cannot decode any original packet from P1 ⊕P6 and the transmission gain that P1 ⊕P6 brings to $R_6$is 0. Therefore, TTG will be 0.9 × 1 + 0.8 × 2 + 0.85 × 1 = 3.35 with IDNC packet P1 ⊕P6.From the example above, we can see that different IDNC packets generated at father benefit different children. If more children can benefit from each retransmission, the number of retransmissions will be reduced, and energy-saving will achieve at father. Thus, how to select or schedule the original packets to form an IDNC packet to make TTG maximum in each retransmission is the critical problem, which is called as PacketScheduling Problem in this research. Packet scheduling problem can be considered as a mixed integer linear programming which is shown in the following:

$$\text{Minimize}(TSN) \equiv \text{Maximize}(G^k),$$

which subjects to

$$\min\{\hat{w}_{i,j}\} \leq G^k \leq \sum_{i=1}^{M}(1-p_i)$$
$$(i = 1, 2, \cdots, M; j = 1, 2, \cdots, N;$$
$$k = N+1, N+2, \cdots, TSN)$$

$$P_c^k = P_{k_1} \oplus P_{k_2} \oplus \cdots \oplus P_{k_K} \quad (1 \leq k_1 \leq \cdots \leq k_K \leq N)$$
$$\hat{w}_{i,j} \in [0, 1) \quad (\forall i = 1, 2, \cdots, M; \forall j = 1, 2, \cdots, N)$$
$$TSN > M,$$

where TSN is the total send number at father.

In the above formulations, the term of the objective represents that minimizing the number or transmissions through maximizing TTG in every round of retransmission.

3.3. Maximize Total Transmission Gain Scheduling of IDNC Packets

It is proved by Wang et al. (2010) that the packet scheduling problemis a nondeterministic polynomial-time hard (NP-hard) problem, and obtaining the optimum solution is so hard and complex. In this section, we propose a packet schedulingscheme to maximize TTG based on WSFM, which is named as MTTG scheme.

The basic ideal of MTTG scheme is selecting the coded packets through WSFM directly. It will be more intuitionistic and efficient compared with those heuristic schemes which try to search maximum clique.

As shown in Figure 3, the realization of MTTG scheme is divided into five stages: Initial transmission, initializing or updating WSFM, IDNC packet scheduling, encoding and retransmitting, and termination. Details of these stages are depicted as follows.

Stage 1. Initial transmission: The initial transmission phase of data dissemination in WSNs. In MTTG scheme, father first broadcasts original packets of a generation to all his children.

Stage 2. Initializing or updating WSFM: After the initial transmission or one round of IDNC packet retransmission, father will initialize or update WSFM. Father collects the packet and PER information from each child through ACK (or NACK) reception and PER estimation. Then, it keeps such information fromall children to initialize or update WSFM. Before the initial transmission phase, we consider WSFM as a matrix containing only '1s'. Father will check whether WSFM is an all '0' matrix. If it is true, it means that all M children obtain N originalpackets successfully and the dissemination of this generation isfinished. Otherwise, go to Stage 3.

Stage 3. IDNC packet scheduling: Father will select or schedule original packets to generate IDNC packet for the kth retransmission. The selected packets will be put into array T. This scheduling is implemented through a packet scheduling algorithm with three steps, which searches IDNC packets in a greedy manner based on WSFM. The packet scheduling algorithm is shown in Algorithm 1.

Step 1: Selecting an original packet $P_h$with maximum TTG in $\{G_k(P_c^k = P_j ; \forall j = 1, 2, \cdot\cdot\cdot, N)\}$. We assign max with this TTG and the corresponding number h is put into T.

Step 2: Two original packets P_m and $P_n$are selected to make G_k maximum in all coded packets that are combined by two original packets. If G_k is larger than max, array T and maxwill be updated with {m, n} and $G_k$respectively. Otherwise, array T keeps unchanged and the search is over.

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Step 3: An original packet Pr is picked to make $G_k$of IDNC packet P_c^k = (⊕i2T Pi) ⊕Pr maximum. If $G_k$is larger than max, max = G_k and r will be joined into T. This step will not stop until max does not increase any longer.

Algorithm 1 Packet scheduling algorithm.

Input: WSFM
Output: T
Begin:
  $G_h^k = \max\{G_i^k, \forall i = 1, 2, \cdots, N\}$;
  $G^k \leftarrow G_h^k$;
  $max \leftarrow G^k$;
  $T \leftarrow \{h\}$;
  for $(m = 1 : N)$
    for $(n = m + 1 : N)$
      if $G^k > max$ //G^k is TTG while $P_c^k = P_m \oplus P_n$
        max $\leftarrow G^k$;
        $T \leftarrow \{m, n\}$;
      endif
    endfor
  endfor
  $mc = 0$ //mc will be used to buffer TTG so far;
  while $(mc < max)$
    $mc \leftarrow max$;
    for $(j = 1 : N, j \notin T)$
      $G \leftarrow G^k$ //G^k is TTG while $P_c^k = (\oplus_{i \in T} P_i) \oplus P_j$;
      if $G > max$
        $max \leftarrow G$;
        $r \leftarrow j$;
      endif
    endfor
    $T \leftarrow T \cup \{r\}$;
  endwhile
end

Figure3:FlowchartofMTTGscheme

	P_1	P_2	P_3	P_4	P_5	P_6	P_7	P_8
R_1	0.9	0.9	0	0	0.9	0	0	0
R_2	0	0	0.8	0	0	0.8	0	0
R_3	0	0	0	0	0	0	0	0.7
R_4	0.85	0	0	0	0	0	0.85	0
R_5	0	0.8	0.8	0	0	0.8	0	0
R_6	0.75	0	0	0	0	0.75	0	0

First selection Second selection Third selection

Figure 4: An example of algorithm 1 based packet scheduling

An example of packet scheduling is shown in Figure 4. In the first instance, the first column is scheduled for TTG of transmitting P1 is 2.5 and maximum in all columns. Then, number '1'is put into array T. In the second scheduling, the first and third columns are selected. TTG of IDNC packet P1 ⊕P3 is 4.1 and maximum in all TTGs of IDNC packets which are combined by two original packets. Hence, array T is updated with {1, 3}. In the third scheduling, the eighth column is chosen from remaining columns as the last selected column. TTG of IDNC packet P1 ⊕P3 ⊕P8 is 4.8 and we can see that there is no other IDNC packets can bring so much gain from ergodic search.

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Hence, the ultimately selected IDNC packets are P1, P3 and P8.
Stage 4. Encoding and retransmitting: Father XORs the original packets selected in Stage 3 and broadcasts IDNC packet to its children. Then, children receive this packet and try to decode an original packet. If an original packet is recovered by a child, it will feed back ACK to father to updateWSFM. If the updated WSFM is not an all '0' matrix, a new round of retransmission will start from Stage 2.
Stage 5. Termination: After all children recover all original packets, i.e., WSFM becomes an all-zeros matrix, the whole data dissemination of this generation is over. If father has more data to be disseminated, it repeats the above stages for another generation.

IV. RESULTS AND DISCUSSION

4.1. Transmission Performance

We firstly analyse the transmission performance with only two children R1 and R2. Assuming that PERs of R1 and R2are p1 and p2 respectively in the dissemination process of a generation and p1 < p2. In addition, we assume a generation contains large enough number of original packets to facilitate our analysis. In initial transmission phase, there are Np1 and Np2 original packets have not been obtained by R1 and R2 averagely.

Generally, one child will be able to decode an original packet in the retransmission phase as long as a packet (coded or not) is received before the data dissemination is over for it. Therefore $\frac{Np_1}{1-p_1}$ and $\frac{Np_2}{1-p_2}$ retransmissions will be requiredby R1 and R2 respectively before the whole delivery is over, and father will perform $\frac{Np_2}{1-p_2}$ transmissions in retransmission phasefor $\frac{Np_1}{1-p_1} \leq \frac{Np_2}{1-p_2}$. From the description above, we can see thatTSN for a generation is determined by the child with maximum
PER. In two child instance, TSN is $N + \frac{Np_2}{1-p_2} = \frac{N}{1-p_2}$ or $\frac{N}{1-\max\{p_1,p_2\}}$.
This result can be extended to the scenario with M(M ≥ 3) children when N is large enough. In this case, the theoreticallow boundary of TSN to deliver N original packets from fatherto M children is

$$TSN = \frac{N}{1-\max_{i\in\{1,2,\cdots,M\}}\{p_i\}}$$

(5)
Then, the average number of transmissions which is denoted as $\overline{TSN}$ is the number of transmissions for each packet averagely, it is defined as follows:

$$\overline{TSN} = \frac{TSN}{N}.$$

(6)
Substituting TSN with (6), we get the boundary of the average
number of transmissions for every packet

$$\overline{TSN} = \frac{1}{1-\max_{i\in\{1,2,\cdots,M\}}\{p_i\}}. \quad (7)$$

4.2. Computational Complexity

In each round of packet scheduling, MTTG, NCWBR, and INCBR schemes firstly check each original packet for M children to see which child has lost this packet. Moreover, if some children miss this packet, father will search all the possible packet combinations. Since there are at most N^2combinations will be searched for M children. Therefore, the packet scheduling algorithm has a time complexity of $O(M \times N^2)$, which is polynomial time and can be implemented practically. However, the MWC scheme transforms WSFM into an adjacent graph which holds at most M × N vertices for search. In a round of packets scheduling, father may search all $(M \times N)^2$combinations. Thus, the algorithm ofMWC scheme has a time complexity of $O(M \times (M \times N)^2) = O(M^3N^2)$, which is much more complex than other three schemes with increase of the generation size and intended children. If we consider PERs into the mathematic expressions of computational complexity, it will be equivalent to substituteM and N with $\frac{M}{1-\max_{i\in\{1,2,\cdots,M\}}\{p_i\}}$ and $\frac{N}{1-\max_{i\in\{1,2,\cdots,M\}}\{p_i\}}$ respectively. Finally, we present computational complexity of the four schemes in Table 3.
Table 3: Computational complexity of four packet scheduling scheme

Scheduling schemes	Computational complexity
MTTG NCWBR INCBR	$O\left(M \times N^2 \times \left(\frac{1}{1-\max_{i\in\{1,2,\cdots,M\}}\{p_i\}}\right)^3\right)$
MWC	$O\left(M^3 \times N^2 \times \left(\frac{1}{1-\max_{i\in\{1,2,\cdots,M\}}\{p_i\}}\right)^5\right)$

4.3. Simulation Results

To verify the effectiveness and efficiency of our MTTG scheme, extensive simulations for performance evaluation are implemented and presented in this section. We compare the performance of MTTG scheme with NCWBR, INCBR and MWC schemes in terms of average number of transmissions and computational overhead (or time) against the changes of the number of packets in a generation, the number of children in a cluster, as well as PERs. Here, computational overhead is used to depict computational complexity. In the process of simulation, PERs on binary erasure channels between father and children are selected randomly from range $\varepsilon-\sigma$ to $\varepsilon+\sigma$, where ε is mean and σ is boundary.

According to equation (8), if the maximum PER is $\varepsilon+\sigma$, the theoretical upper boundary of average number of transmissions can be derived as follows:

$$TSN_{Upbound} = \frac{1}{1-(\varepsilon+\sigma)}$$

(8)

4.3.1. Average Number of Transmissions in Cluster

The impact of children number is first evaluated. Packet number and PER on average number of transmissions in Figures 4 - 6. Figure 4 depicts the average number of transmissions with the change of children number in a cluster (N = 100, ε = 0.3, σ = 0.1). From this, we can draw the following observations:

- ✓ the number of transmissions increases with increase of children number, and NCWBR scheme's performance deteriorates rapidly. It shows the necessity to divide a large-scale WSN into small-scale clusters.
- ✓ Maximum TTG (MTTG) and MWC schemes achieve much better performance. For the MTTG and MWC schemes, the average transmission numbers increase a little and maintain relatively high transmission efficiency yet with increase of children.

Figure 5 depicts the average number of transmissions comparison of MTTG scheme with other three schemes against the number of packets in a generation (M = 10, ε = 0.3, σ = 0.1). From this, we can clearly see that, MWCscheme outperforms other schemes and MTTG scheme is suboptimal. The number of transmissions of MTTG, MWC and INCBR schemes decreases with increase of packet number as the coding opportunities increase. However, the performance of NCWBR scheme is almost invariable and is the worst in all schemes.

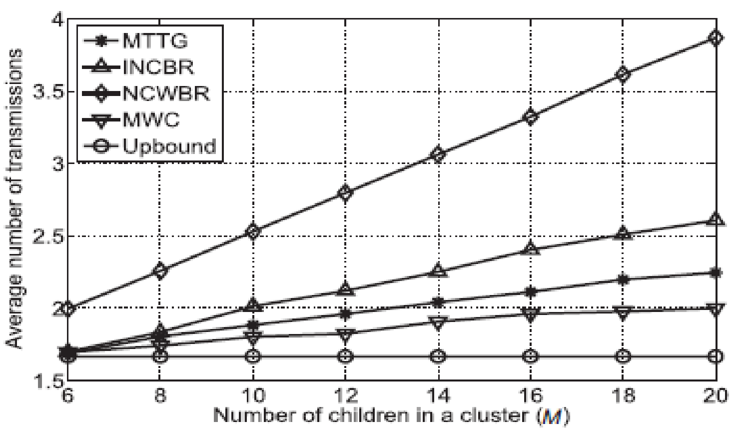

Figure 4:Evaluate performance of average number of transmissions against M, N and average packet erasure ratio: average number of transmissions against children number, where N = 100, " = 0.3, σ = 0.1

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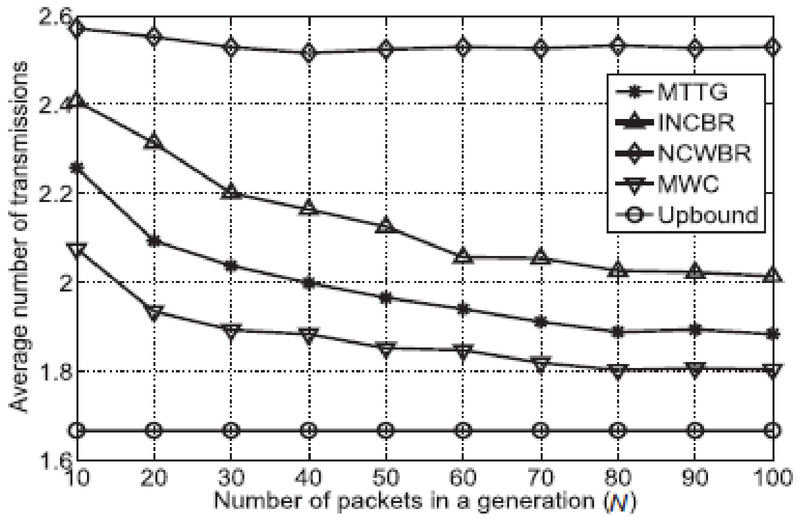

Figure 5: Evaluate performance of average number of transmissions against M, N and average packet erasure ratio:average number of transmissions against packet number, where M = 10, " = 0.3, σ = 0.1,

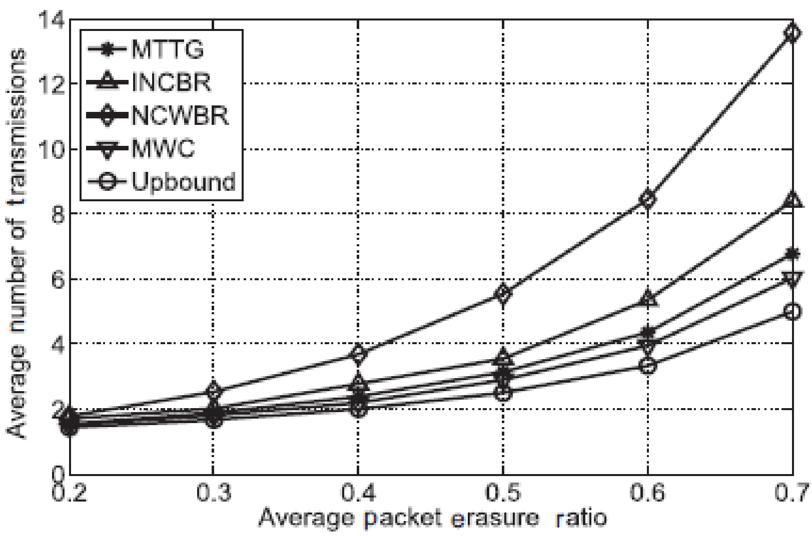

Figure 6: Evaluate performance of average number of transmissions against M, N and average packet erasure ratio:average number of transmissions against average packet erasure ratio, where M = 10, N = 100, σ = 0.1

Figure 6 compares the average number of transmissions of our proposed scheme to other three schemes with the change of average packet erasure ratio (M = 10, N = 100, σ = 0.1). The number of transmissions increases exponentially with increase of PERs for all the four schemes. However, the performance of MTTG and MWC schemes is much better than NCWBR and from Figure 5 we can see that the performance improvement of MTTG scheme compared with INCBR scheme is only 5%when the number of children in a cluster is small and PER is not large, which seems not significant. However, it is shown in Figures5 and 6 that this improvement will become notable with increase of children number and PERs. The improvement with M = 20, N = 100 and ε = 0.3 is over 17% and with M = 10, N = 100, ε = 0.7 is over 21%. It means that our MTTG scheme can improve transmission efficiency further than

INCBR scheme when the scale of cluster is large enough and the link status is not good. In addition, we make some simulations for the PER is constant (ε = 0.3, σ = 0) and changes in a large range (ε = 0.5,σ = 0.4) to validate the transmission performance in differentnetwork environments. Figures 7 and 8 show the average number oftransmissions on condition that PER is constant.We can see thatthe performance of MTTG scheme outperforms other schemeseven MWC scheme. The reason is that a few coding opportunitieshave been dropped to fulfill the instant decodability for all selected vertices in MWC scheme. However,MTTG schemeaims at maximizing the transmission gain even some selected children cannot recover any original packets.Transmission performance on condition that PERs change in a large range is shown in Figures 9 and 10. It shows that the performance ofMTTG and MWC schemes is better than INCBR and NCWBRschemes. From the figures we can see that the average numberof transmissions may be less than the theoretical upper boundary.This is due to the fact that PERs are randomly selected from a largerange which may be much smaller than the upper boundary 0.9especially when a few children in the cluster.

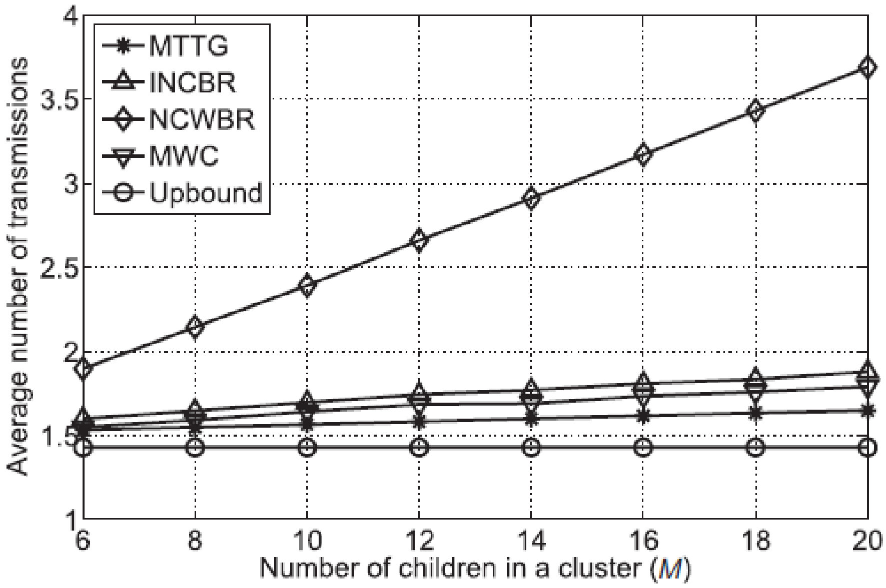

Figure 7:Evaluate performance of average number of transmissions against M and N with PER is constant: average number of transmissions againstchildren number, where N = 100, PER=0.3

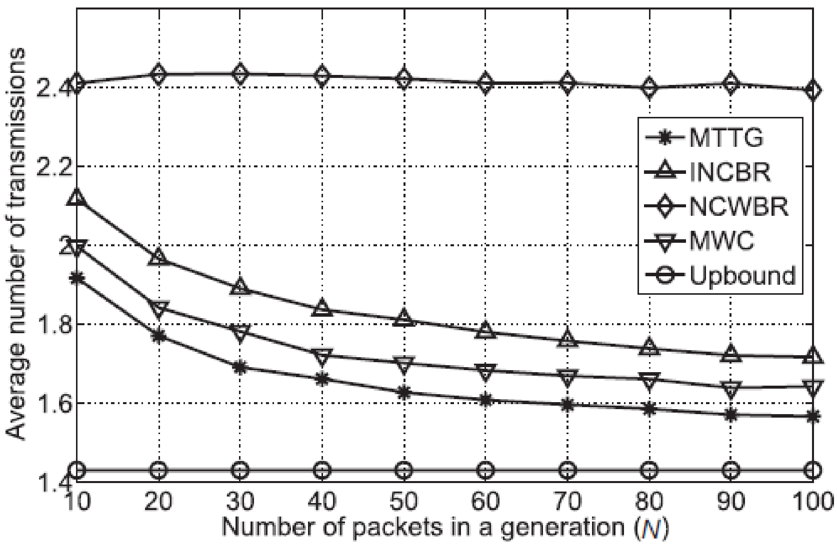

Figure 8: Evaluate performance of average number of transmissions against M and N with PER is constant: average number of transmissions against packet number, where M = 10, PER=0.3.

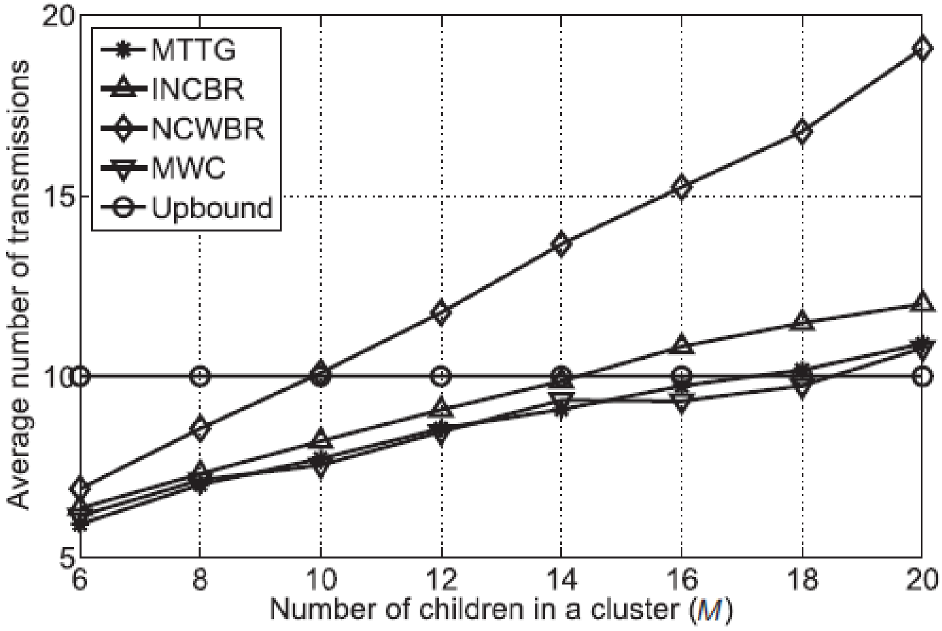

Figure 9: Evaluate performance of average number of transmissions against M and N with PER changing in large range: (a) Average number of transmissionsagainst children number, where N = 100, PER∈[0.1, 0.9]

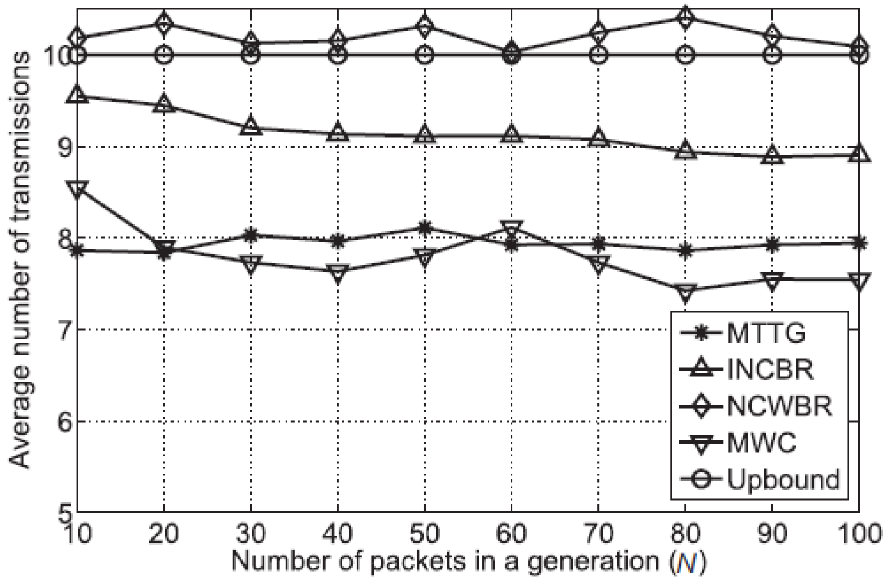

Figure 10:Evaluate performance of average number of transmissions against M and N with PER changing in large range: average number of transmissions against packet number, where M = 10, PER∈[0.1, 0.9]

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V. CONCLUSION

In the course of this research, we investigated data dissemination in WSNs to achieve transmission and energy efficiency. Cluster-tree based network architecture has been proposed to implement the data dissemination through multihop decode-encode-forward. However, link loss, fading, interference and node sleep result in packet erasure and degrade the delivery performance greatly. Considering the limited storage and processing capability at sensors in WSNs, it is important to develop high efficiency and low-complexity approach. Issues involving privacy and anonymity of users trying to access real time data of the wireless sensor nodes, will need more attention since existing protocols are prone to denial-of-sleep attack. Also, in the application of WSNs to medicine and industries, how best can the sensitive and confidential information be transmitted so as to prevent external intrusion? What additional roles will WSNs play in the emerging Internet of Things (IoT) paradigm? Solutions to questions like this will require more research efforts in order to enhance user's confidence and lead to more innovative applications.

In order to quicklycomplete the whole process of data dissemination and reduce the decoding overhead, we propose a novel MTTG scheme based on IDNC, which targets to maximize total transmission gain in each retransmission with low computational complexity. A packet scheduling algorithm based on WSFM is proposed to select IDNC packets in each round of retransmission in a cluster.

Packet erasure ratio has been considered in the performanceanalysis and we derive the upper boundary of the number of transmissions for a generation as well as the computational complexity of each scheme. Extensive simulations are conducted to assess the performance of the proposed scheme compared to the existing schemes. The simulation results show that our MTTG scheme achieves efficient delivery while keeps a low complexity. However, cluster partition and father election are not the emphasis in this paper and they will be presented in our futurework.

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