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Achieving Energy Saving in Wireless Sensor Networks through CRT-Packet Forwarding Solution

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Abstract

This paper deals with a novel forwarding scheme for wireless sensor networks aimed at combining low computational complexity and high performance in terms of energy efficiency and reliability. The proposed approach relies on a packet-splitting algorithm based on the Chinese Remainder Theorem (CRT) and is characterized by a simple modular division between integers. An analytical model for estimating the energy efficiency of the scheme is presented, and several practical issues such as the effect of unreliable Channels, topology Changes, and MAC overhead are discussed. The results obtained show that the proposed algorithm outperforms traditional approaches in terms of power saving, simplicity, and fair distribution of energy consumption among all nodes in the network.

Keywords: *Chinese Remainder Theorem, energy efficiency, packet splitting, reliability, wireless sensor networks.*

1. Introduction

A wireless sensor network (WSN) is composed of a large number of low-cost devices distributed over a geographic area. Sensor nodes have limited processing capabilities, therefore simplified protocol architecture should be designed so as to make communications simple and efficient. Moreover, usually the power supply unit is based on an energy-limited battery, therefore solutions elaborated for these networks should be aimed at minimizing the energy consumption. To this purpose, several works have shown that energy consumption is mainly due to data transmission, and accordingly energy conservation schemes have been proposed aimed at minimizing the energy consumption of the radio interface [1], [2], [10].

With the aim of reducing energy consumption while taking the algorithmic complexity into account, we propose a novel approach that splits the original messages into several packets such that each node in the network will forward only small subpackets. The splitting procedure is achieved applying the Chinese Remainder Theorem (CRT) algorithm [14], which is characterized by a simple modular division between integers. The sink node, once all subpackets (called CRT components) are received correctly, will recombine them, thus reconstructing the original message. The splitting procedure is especially helpful for those forwarding nodes that are more solicited than others due to their position inside the network. Regarding the complexity, in the proposed approach, almost all nodes operate as in a classical forwarding algorithm and, with the exception of the sink, a few low-complex arithmetic operations are needed. If we consider that the sink node is computationally and energetically more equipped than the other sensor nodes, the overall complexity remains low and suitable for a WSN. Moreover, the proposed technique does not require the use of disjoint paths.

Some preliminary results of this approach have been presented in [4], but they were empirical only and obtained through simulations on a sensor network where it is assumed that an ideal communication among neighbor sensors occurs, and all the CRT components can be received correctly. Obviously, this hypothesis is not valid in a real network. Consequently, in [5], some considerations about a more realistic WSN scenario have been introduced.

In this paper, we present a comprehensive framework in which we provide a thorough analytical model that allows us to derive some accurate results regarding energy consumption and complexity. Also, we introduce some main considerations about the implementation of the proposed technique in a real sensor network, i.e., by taking into account erasure channels, MAC-layer overhead, and actual computational resources of nodes. Furthermore, we discuss the effect of important parameters such as nodes' density and transmission range through both extensive simulations and an analytical study of the tradeoff between energy saving, complexity, and reliability of the proposed technique.

2. Related Works

Energy saving, reliability, and complexity are three key issues in WSNs.With regards to energy saving, two main approaches can be found in the literature: duty cycling and in-network aggregation; see [2] and [10], respectively. The first approach consists in putting the radio transceiver on sleep mode (also known as power-saving mode) whenever communication is not needed. Although this is the most effective way to reduce energy consumption, and energy saving is obtained at the expense of an increased node complexity and network latency. The second approach is intended to merge routing and data aggregation techniques and is primarily aimed at reducing the number of transmissions.

An interesting example of using a multipath approach together with erasure codes to increase the reliability of a WSN has been proposed in [9]. However, in that work, the authors suggested the use of disjoint paths. When compared to our proposed forwarding technique, using disjoint paths has two main drawbacks. First, a route discovery mechanism is needed. Second, as the numbers of disjoint paths are limited, the numbers of splits (and therefore the achievable energy reduction factor) are limited as well. Furthermore, in [9], the authors considered general forward error correction (FEC) techniques without investigating their specific complexities and/or their impact on energy consumption.

Another similar work is [7], where the authors have proposed a protocol called ReInForM (Reliable Information Forwarding using Multiple paths in sensor networks). The main idea investigated in this paper is the introduction of redundancy in data to increase the probability of data delivery. The redundancy adopted is in the form of multiple copies of the same packet that travel to the destination along multiple paths. However, as shown in [12], multiple paths could remarkably consume more energy than the single shortest path because several copies of the same packet have to be sent. An attempt to guarantee reliability, while minimizing the energy consumption and, at the same time, considering a packet-splitting procedure, has been made in [8].

In this paper, we show that by using the CRT-based approach, both reliability and energy saving can be achieved with a moderate increase in the overall complexity and with very low overhead as compared to the commonly used forwarding techniques.

3. CRT-Based Forwarding Technique

In this section, we briefly outline the CRT and show how to use it to implement a new forwarding technique that is both reliable and energy-efficient.

3.1. Chines Remainder theorem

Basically, in its simpler form, the CRT can be formulated as follow s [14]: Given primes $P_i > 1$,with $i \varepsilon \{ 1 \ldots N \}$ by considering their product $M = \pi_i \mathrm{p_i}$,then for any set of given integers, $\{m_1, m_2 \ldots\ldots\ldots\ldots, m_N\}$, there exists a unique integer $m < M$ that solves the system of simultaneous congruences $m = m_i$ $(mod\ p_i)$ and it can be obtained by $m = (\sum_{i=1}^{N} c_i \ .\ m_i)$ The coefficients c_i are given by $c_i = Q_i q_i$, where $Q_i = M / p_i$, and q_i is its modular inverse, i.e., q_i solves $q_i Q_i = 1 (mod\ p_i)$

For instance, let us consider the system: m = 1(mod 3); m=4 (mod 5): m=1 (mod 7).It is simple to prove that m=64 solves the system and that it can be obtained through the above equations (in fact, we have M=105: $c_1=70$, $c_2=21$, $c_3=15$,and m=64).

3.2. Metrics for Energy Efficiency

According to the CRT, the number can be alternatively identified with the set of numbers provided that are known. However, it is worth noting that in the above example, Therefore if, instead of *m*, m_i

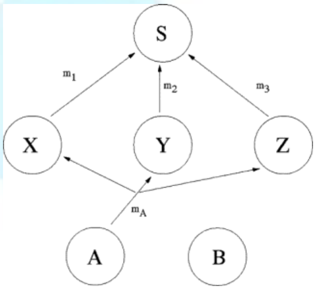

Fig. 2. Example of forwarding after splitting

Fig.2.Example of forwarding after splitting numbers, with $m_i = m (mod\ p_i)$, are forwarded, the maximum energy consumed by each node for the transmission can be substantially reduced.

For instance, consider Fig. 2. If X, Y, and Z receive a message m_A from A, each of them, applying the procedure shown above can transmit a message m_i, with $i \varepsilon \{1,2,3\}$, to the sink instead of m_A Furthermore, the sink, knowing p_i, with $i \varepsilon \{1,2,3\}$, and using the CRT approach, will be able to reconstruct m_A, In general, if we consider that the energy consumption is proportional to the maximum number of bits transmitted,

and assuming ω as the number of bits in the original message m, and as the ωCRT_{MAX} maximum number f bits of a CRT component, i.e., $\omega CRT_{MAX} = \max([\log_2(p_i)])$, we can consider a theoretical maximum energy reduction factor (MERF) given by

$$MERF = \omega - \omega CRT_{MAX} / \omega$$

For instance, in the previous example, MERF = 7-3/7 ≈ 0.57.This means that about 57% of the needed energy could be saved by considering the proposed forwarding scheme.

The previous energy reduction factor can be obtained when all the CRT components, m_I are forwarded by different nodes (i.e., for disjoint paths). In a real scenario, where the CRT components are not always forwarded through disjoint paths, the MERF is rarely obtained, and the expected energy reduction factor (ERF) has to be expressed taking into account both the actual number of bits forwarded by a traditional forwarding algorithm and our proposed CRT-based forwarding algorithm, under the same conditions.

3.3.On the Choice of the Prime Numbers

It is important to observe that the set of prime numbers $p_i > 1$, with $i \varepsilon \{1 \ldots N\}$, can be arbitrarily chosen provided that m < M. Therefore, the number of bits needed to represent m_i can be reduced by choosing the prime numbers as small as possible. As a consequence of this choice, the MERF is maximized.

The MERF in this case is 0.725. However, when the primes set are chosen as above, the message can be reconstructed if and only if all the CRT components are correctly received by the sink.

Let us consider another prime set {10313, 10321, 10331, and 10333}.These is the smallest consecutive primes that satisfy the condition even if one of primes is removed. We call this set the Minimum Primes Set with one admissible failure (the name will be better clarified below), and we will indicate it as MPS-1. In general, throughout the paper we will indicate with MPS-f the Minimum Primes Set with f admissible failures.

When compared to the previous MPS, it is possible to observe the following.

- The number of components is not changed (i.e., the same number of forwarders is needed).
- The MERF obtained with the new set is 0.65, i.e., MERF is reduced by about 11%. However, with this choice it is possible to reconstruct the original message *m* even if a component is lost (i.e., if we have one failure). In fact, whatever the lost component is, the product of the primes associated with the received components satisfies the condition

$M' = \pi_{i \neq j} p_i > 2^{40}$, and therefore it respects the hypothesis of the CRT theorem.

3.4 Forwarding Algorithm

The forwarding algorithm is based on two temporal phases, the Initialization phase and the Forwarding phase.

1) Initialization Phase: This phase organizes the network in clusters and also has the advantage of minimizing the number of hops needed to reach the sink.

The Initialization phase has been described in detail in [5], and it is realized through an exchange of initialization messages (IMs) starting from the sink that is supposed to belong to the cluster 1, i.e., $CL_{ID} = 1$, where CL_{ID} identifies the cluster number. Each node that receives an IM from its neighbors with a sequence number SN = h, will belong to cluster h and will

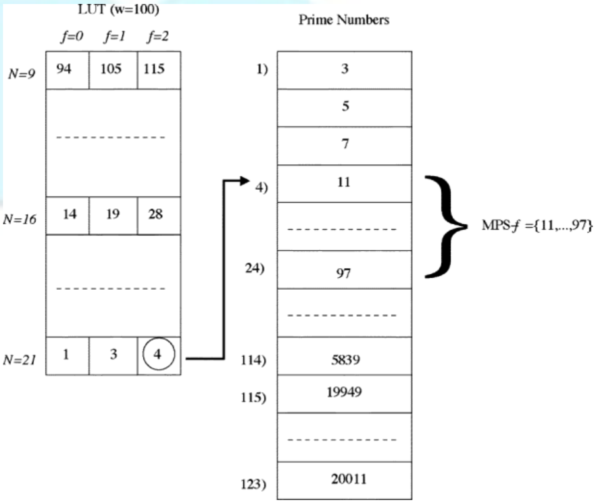

Fig. 3. Example of computation of the MPS-f.

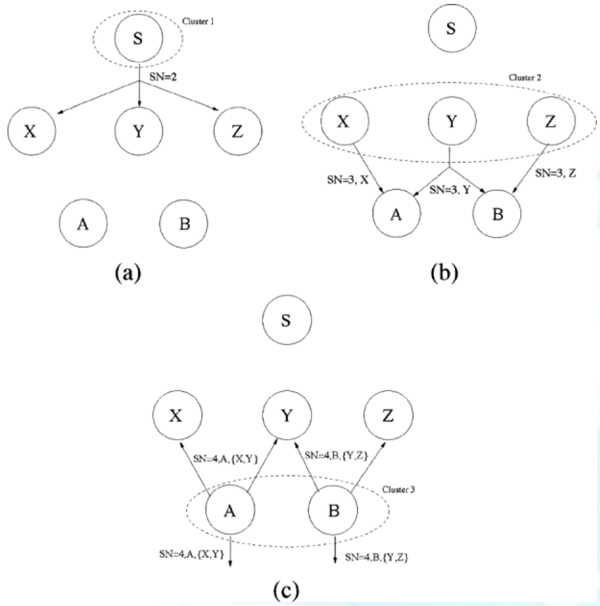

Fig. 4. Initialization procedure. (a) Sink sends the first IM. (b) Nodes X, Y, and Z belong to $CL_{ID} = 2$. (c) Node X knows that A will use X and Y as next-hops and therefore that all packets originated by A can be split in N_A parts.

retransmit the IM with an increased SN together with its own address and the list of the nodes that will be used as forwarders (that it knows on the basis of the source addresses specified in the received IMs). On the basis of the received IMs, at the end of the procedure each node in the network will know its own next-hops, which other nodes will use it as a next-hop, and into how many parts the received packets can be split (see Fig. 4 for a simple example).

2) Forwarding Phase: Once the network has been organized, the Forwarding phase is applied.

Basically, all nodes follow the same forwarding rule: *If* there is a number of neighbors at least equal to N, and the packet has not previously split, *then* split the packet; *else* use conventional shortest path approach. Let us consider the network shown in Fig. 5, where clusters are obtained according to the initialization procedure already described in the previous section. The figure shows the messages sent by each node when the source node H sends a message *m* to the sink S.

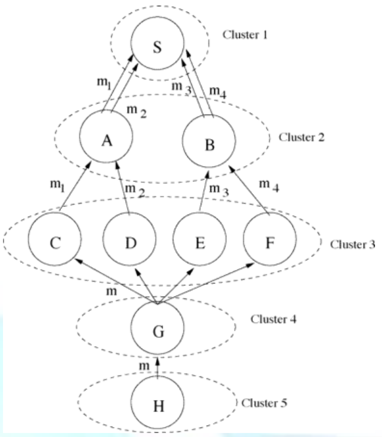

Fig.5. Forwarding example

According to the initialization procedure, node G knows that it is the only next-hop of node H, and therefore it must forward the packet without performing a splitting procedure. It is worth highlighting that it is not necessary for G to specify the list of the destination addresses {C, D,E,F} in the packet. In fact, in the initialization phase, nodes {C, D, E, F} have already received the IM message IM : [SN=5,G, {C, D, E, F}], and therefore they know that node G has four next-hops and that all of them have to split the messages received from G into $N_G = 4$ parts.

Therefore, when they receive the packet, according to both the packet size, *w*, and N_G, they independently select the prime numbers[3] and send the components $m_i = m \pmod{p_i}$, together with a proper mask, to one of the possible next-hops. When the sink receives a component m_i, it identifies the number of expected components on the basis of the mask, and therefore it calculates the MPS-*f* and the coefficients c_i needed to reconstruct the original message. Finally, when the sink receives at least $N_G - f$ components of the original message, it can reconstruct the message by $m = \sum_I c_i m_i \pmod{M'}$. Note that because the events that happen in a sensor network may change, in number and locations, during the time period considered, consequently the packets can be generated by different nodes, and the components (m_i) received and transmitted by the nodes change accordingly. Thus, for different source nodes, any node transmits CRT components based on different prime numbers.

Concerning the complexity of the algorithm, it is worth mentioning that the message splitting is performed only one time by the nodes that are the closest to the source and have the opportunity to do it (e.g., if they are in proximity of a number of neighbors higher than the threshold specified for the initialization phase), whereas the other sensor nodes in the network will just forward the subpackets. Moreover, only the sink node will reconstruct the original message through more complex operations as described, but this can be neglected if we consider that usually the sink node is computationally and energetically more equipped than the other sensor nodes. Obviously, in the case of very large packets, it is possible to split the packets recursively, but in order to keep the complexity of the proposed algorithm very low, we will consider that a packet can be split only one time.

4. Performance Evolution

In this Section we show a comparison between the results obtained through the analysis reported in the previous section and those obtained through a custom NS-2 simulator. For the sake of space we report simulation results for a specific case study but several simulations have been carried out with similar results.

The bit error rate or bit error ratio (BER) is the number of bit errors divided by the total number of transferred bits during a studied time interval. BER is a unitless performance measure, often expressed as a percentage. the bit error probability p_e is the Expectation value of the BER. The BER can be considered as an approximate estimate of the bit error probability. This estimate is accurate for a long time interval and a high number of bit errors.

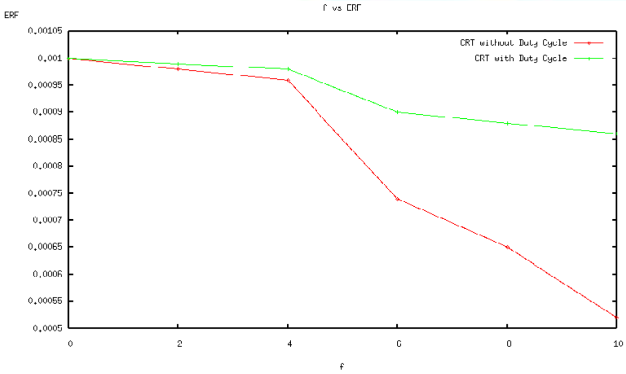

Fig. a. Bit error rate

If you want to evaluate the performance of protocol using NS-2, first you have to define the evaluation criteria. This time I want to explore about Packet delivery ratio, packet lost and end to end delay. Packet delivery ratio: the ratio of the number of delivered data packet to the destination. This illustrates the level of delivered data to the destination.

∑ Number of packet receive / ∑ Number of packet send

The greater value of packet delivery ratio means the better performance of the protocol. End-to-end Delay : the average time taken by a data packet to arrive in the destination. It also includes the delay caused by route discovery process and the queue in data packet transmission. Only the data packets that successfully delivered to destinations that counted.

∑ (arrive time – send time) / ∑ Number of connections

The lower value of end to end delay means the better performance of the protocol. Packet Lost: the total number of packets dropped during the simulation.

Packet lost = Number of packet send – Number of packet received.

The lower value of the packet lost means the better performance of the protocol.

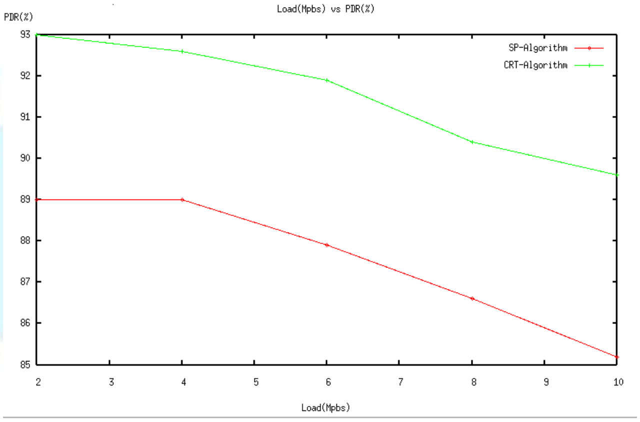

Fig. b. Packet delivery ratio

bit rate (sometimes written bitrate or as a variable $R^{[1]}$) is the number of bits that are conveyed or processed per unit of time. The bit rate is quantified using the bits per second (bit/**s**) unit.

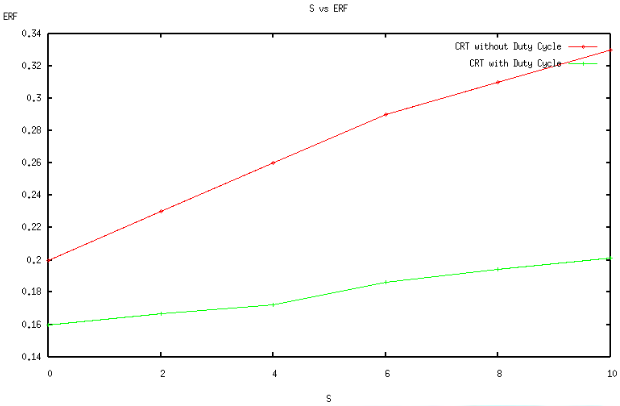

Fig. c. bitrate

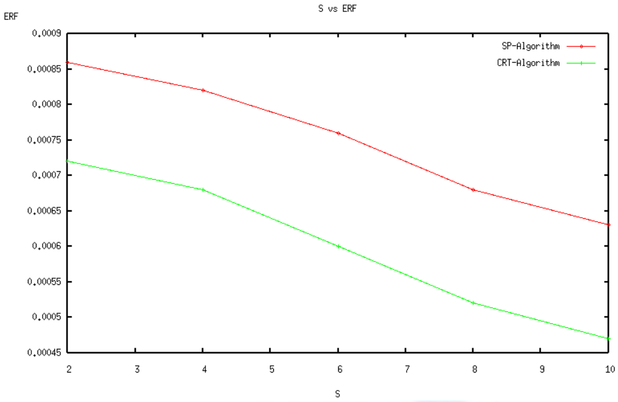

Fig. d. bitrate (simulation time)

delay also refers to the process of broadcasting an event at a later scheduled time. This is because either a scheduling conflict prevents a live telecast, or a broadcaster seeks to maximize ratings by airing an event in a certain timeslot.

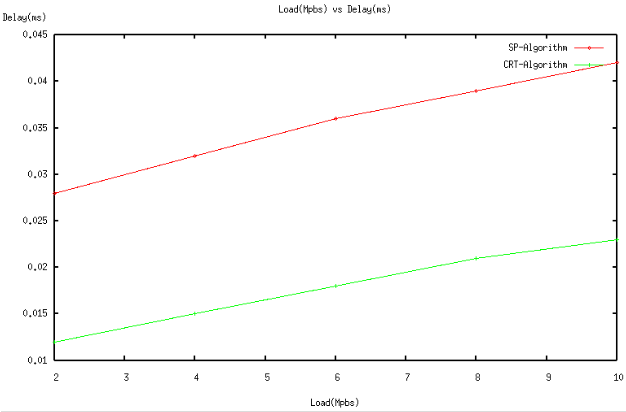

Fig. e. Delay

5. Conclusion

In this paper, we have presented a novel forwarding technique for WSNs based on the Chinese Remainder Theorem (CRT). In particular, we have derived an analytical model able to predict the energy efficiency of the method, and we have especially focused on some implementation issues.

First, we have discussed the choice of the CRT algorithm parameters in order to keep the processing complexity low, then we have derived a tradeoff between energy consumption and reliability.

Finally, we have investigated the overhead introduced in terms of packet header size. Simulation results have confirmed the results obtained analytically and have shown that applying the CRT-based technique significantly reduces the energy consumed for each node, and consequently increases the network lifetime.

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