Data aggregation in Wireless Sensor Networks: Compressing or Forecasting?

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Abstract

Data aggregation is a key problem in wireless sensor networks due to both energy-constrained and bandwidth-constrained. In this paper, we highlight the aggregation benefits in network layer and MAC layer by modeling the energy consumption for some energy-efficient routing protocols and MAC protocols. Besides, we define two parameters, aggregation ratio w and packet size coefficient λ, to evaluate the efficiency of an aggregation method, and we discuss their trade-off. Additionally, we propose comparison between A-ARMA and compressive sensing, which are on behalf of the state-of-the-art forecasting aggregation and compressing aggregation respectively.

1 Introduction

Energy and network capacity always limit the performance of application in wireless sensor networks because sensor nodes are energy constrained and bandwidth constrained. Nevertheless more and more applications require longer lifetime and more network capacity which leads to many energy-efficient routing protocols [1][2][3][4] and MAC protocols [5][6][7]. However, under general assumptions, these protocols exhibit, more or less, the same performance because whatever the routing/mac protocols are, when the application has a data to send, a packet should transmitted, and the energy consumption to transmit one packet is more or less the same. In wireless sensor networks, data aggregation is defined as the process of aggregating the data from no less than one sensor to eliminate redundant transmission and to provide fused information to the sink (in case of one sensor, it can be also considerably reduce the redundant information due to the temporal correlation). In this paper, numerical results highlight that data aggregation save more energy and capacity regardless of routing or MAC protocols. Besides, we introduce two parameters, **aggregation ratio** w and **packet size coefficient** λ, to evaluate aggregation strategies.

Aggregation strategies can be divided into two types: compressing-based aggregation [8][9] and forecasting-based aggregation [10]. Compressing-based aggregation focuses on compressing the data during the procedure of data gathering, which reduce the amount of packets to achieve the goal of reducing traffic. Forecasting-based aggregation tends to use mathematical model to predict and reduce the data reporting frequency, taking benefit from either temporal or spatial correlation between data. In this paper, we give an overview of these two methods, and more specifically we consider A-ARMA [10] and compressive sensing [8][9].

The rest of paper is organized as follow. Prior data aggregation techniques are reviewed in Sec. 2. The aggregation benefits in routing (*resp.* MAC) layer are shown in Sec. 3 (*resp.* Sec. 4). The trade-off between aggregation ratio and packet size coefficient to select the right aggregation method is discussed in Sec. 5. Sec. 6 is focused on the comparison between A-ARMA and compressive sensing. Finally, Sec. 7 concludes the paper.

2 Related works

Compressing-based aggregation focuses on compressing the data during the procedure of data gathering, which recently uses the theory of compressive sensing (CS)[11]. Compressive Sensing asserts that some signals can be recovered from fewer samples than Shannon sampling uses [8][9]. Suppose if a signal $d \in \mathbb{R}^N$can be represented as a sparse signal $x \in \mathbb{R}^N$ in some orthonormal basis $\Psi \in \mathbb{R}^{N\times N}$, the signal can be recovered from M ($M \ll N$) measurements. The sampled signal via CS can be presented as:

$$y = \Phi d + e = \Phi \Psi x + e$$

where $\Phi \in \mathbb{R}^{M\times N}$represents a sensing matrix and e is an unknown additive noise during acquisition. CS theory shows that in general, $\mathcal{O}(k \log \frac{N}{k})$ random measurement are enough to recover a signal (when the signal is k-sparse), and chosen $M = 3k$ as the number of measurements. The first complete design to apply CS theory to data gathering for large-scale wireless sensor networks is presented in [8]. They show that when data are transmitted taking benefit from CS theory, it leads to bottleneck decreasing and network capacity increasing.

Forecasting-based aggregation in WSN tends to use mathematical model to forecast (due to the high temporal correlation in time series) and reduce the data reporting frequency. In general, the basic model has been used in forecasting is Auto Regression Moving Average(ARMA) [11]. Adaptive ARMA (A-ARMA) extends this work using a fixed-size window to reduce the computation of parameters in sensors [10]. If the accuracy of the given parameters is correct according to the given threshold, there is no traffic in network because the sink can recover the data by ARMA model.

3 Routing layer-benefits from aggregation

3.1 Basic topology analysis

Three network topologies are considered to discuss the energy consumption and network capacity: 1-hop network, 1D network and 2D network. In 1-hop network, every sensor (we set 5 sensors) is directly connected to the sink, and any two nodes cannot communicate with each other. In 1D network, every sensor can communicate only with his direct neighbours. In 2D network, we consider a classical grid network. In each scenario, we assume that each node has data packet to send to the sink. These topologies are shown in figure 1.

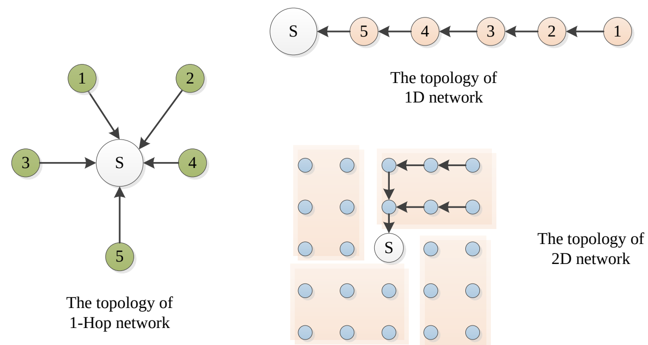

Figure 1: The three different topologies

We define two parameters, **aggregation ratio** (w) [1] and **packet size coefficient** (λ) [2]. These parameters are helpful to evaluate the ability of aggregation to save energy and capacity. For numerical results, we assume that the power of transmission (*resp.* reception) is $P_{tx} = 62.5mW$ (*resp.* $P_{rx} = 53.7mW$), and the packet size is 100 bytes.

In 1-hop network, assuming a sensor generates 30 packets, temporal correlation is used to aggregate. Setting $w_{1h} \in [0.1, 1]$ as the aggregation ratio range

[1] **Aggregation ratio** $w \in (0, 1]$ is the rate of packets effectively transmitted. $w = \frac{n}{N}$ where n is the number of transmitted packets (considering aggregation), while N is the total packets generated. Thus only w% of the generated packets are really transmitted. $w = 1$ means there is no aggregation. The smaller w is, the smaller number of required packets, the higher correlation.

[2] **Packet size coefficient** $\lambda \in [-1, 1]$ is the rate of the packet size change. If p is the original packet and p' is the aggregated packet size, thus $\lambda = \frac{p' - p}{p}$. Note, λ can be negative if the aggregated packet size is smaller than the original one. $\lambda = 1$ means the new packet size is as twice as the original one (If the packet size increases more than 100%, it will lead to packet loss or traffic congestion. Thus we don't consider the situation of $\lambda > 1$).

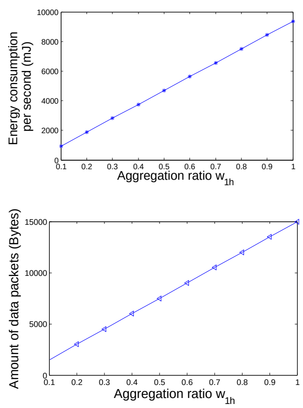

Figure 2: Energy consumption and network capacity considering different aggregation ratio w_{1h} in 1-hop network

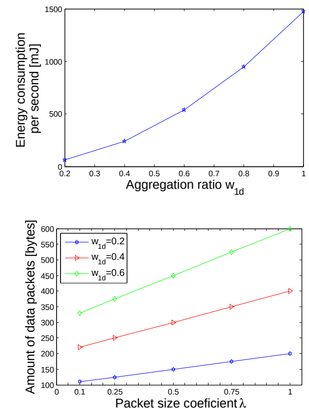

Figure 3: Energy consumption and network capacity considering different aggregation ratio w_{1d} and packet size coefficient λ in 1D network

in the 1-hop scenario. The energy consumption can be written as $5 \cdot P_{tx} \cdot 30 \cdot w_{1h}$. Similarly, the capacity consuming is $500 \cdot 30 \cdot w_{1h}$, as shown in figure 2 (a) and (b). It is obviously that the higher temporal correlation, the less the aggregation ratio, the whole network consumes less energy and saves more capacity.

In 1D network, every node generates 1 packet, spatial correlation can be used to execute aggregation. If there is no correlation in nodes, the energy consumption for the network is $\sum_{i=1}^{5}[i \cdot P_{tx} + (i-1) \cdot P_{rx}]$, where i is the sensor number. Setting aggregation ratio $w_{1d} \in [0.2, 1]$, thus the energy consumption is $\sum_{i=1}^{5w_{1d}}[i \cdot P_{tx} + (i-1) \cdot P_{rx}]$ (figure 3(a)).

For capacity in 1D network, we examine the effects of packet size change on the capacity because aggregation may increase the size of packet (note: we do not discuss the case of packet size decreasing, see section 5). We set packet size coefficient $\lambda = 10\%, 25\%, 50\%, 75\%$ and 100%. The maximum link capacity without aggregation ($w_{1d} = 1$) is 500 bytes. When $w_{1d} < 1$, the link capacity can be formulated as $100 \cdot 5 \cdot w_{1d}(1 + \lambda)$ (figure 3(b)). Note that if the link capacity is saved, the network capacity will be saved obviously.

In the 2D network, we assume every node routes only 1 packet to the sink using a shortest path routing protocol (e.g., Dijkstra). We can divide the traffic flows into 4 parts (see fig. 1). For one part, the energy consumption is $15 \cdot P_{tx} + 9 \cdot P_{rx}$. Thus the whole energy consumption is $60 \cdot P_{tx} + 36 \cdot P_{rx}$. With aggregation ratio $w_{2d} \in [0.2, 1]$, the energy consumption is $w_{2d} \cdot (60 \cdot P_{tx} + 36 \cdot P_{rx})$ (figure 4(a)).

As for the 2D network, the capacity is also correlated to the pack size coefficient. We consider the link between sink and the directly connected node, since the traffic along this link is the highest. The maximum link capacity without aggregation ($w_{2d} = 1$) is 600 bytes. When $w_{2d} < 1$, the link capacity can be formulated as $100 \cdot 6 \cdot w_{2d}(1 + \lambda)$ (figure 4(b)).

We conclude that proportionally to the aggregation efficiency, link capacity is saved (see fig. 3(b) and 4(b)). For the values ($w = 0.6, \lambda > 75\%$), the link capacity is higher than the original capacity, but along with the packet size coefficient decreases, the capacity is saved: we need to investigate the trade off between the packet size and the aggregation ratio (see section 5).

3.2 Routing protocols

In the context of WSN, routing protocols should save energy and, then, extend the network lifetime, (e.g.,

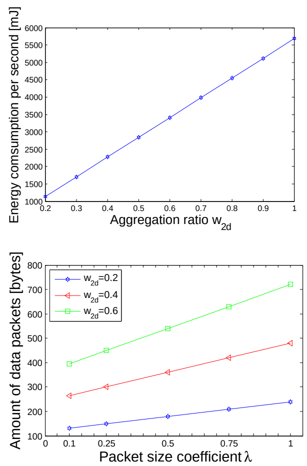

Figure 4: Energy consumption and network capacity considering with different aggregation ratio w_{2d} and packet size coefficient λ in 2D network

OLSR[3], GPSR [4], GBR [1], Simple Random Walk (SRW)[2]). Note that, as data aggregation, the goal of such routing protocol is also to save energy. However, by modeling the energy consumption for the mentioned protocols, we show that data aggregation is always the most basic way to save energy.

Several analytical models were proposed to model energy consumption in battery-powered WSN. We use the model described in [12] as the model for energy consumption for both transmission and reception, and formulated as:

$$E_b = E_{T_x} + \Gamma \times E_{R_x} \tag{1}$$

where E_{T_x} is the energy consumed to transmit 1 bit; E_{R_x} is the energy consumed to receive the same bit at targeted receivers; Γ is the neighborhood size. Actually, E_b denote the total energy cost of a single bit in 1-hop transmission, including transmission and reception costs.

We use the models given in [12]:

$$E_{OLSR} = E_H + E_{TC} + E_D \triangleq f_{OLSR}(E_b)$$

$$E_{GPSR} = E_H + E_D + E_{PU} \triangleq f_{GPSR}(E_b)$$

$$E_{GBR} = E_{ADV} + E_D \triangleq f_{GBR}(E_b)$$

$$E_{SRW} = E_H + E_D \triangleq f_{SRW}(E_b)$$

where E_D is the energy consumption for data message, and others are the control messages [11]. Although these protocols use different routing strategies, e.g., proactive routing, gradient routing or geographic routing, the energy consumption is more or less similar (the only difference is the control messages), and all the energy consumptions are proportional to E_b. Regarding E_b, Eq. 1 shows that the dominant factors are E_{T_x} and E_{R_x}. The purpose of aggregation is to exactly reduce the traffic, which is the fundamental way to reduce the energy consumption in transmission and reception.

If we assume an aggregation method with aggregation ratio w, thus the function of energy cost is redefined as:

$$f'_{OLSR}(E_b) = w f_{OLSR}(E_b) = w E_{OLSR}$$

$$f'_{GPSR}(E_b) = w(E_H + E_D) + E_{PU}$$

$$f'_{GBR}(E_b) = w f_{GBR}(E_b) = w E_{GBR}$$

$$f'_{SRW}(E_b) = w f_{SRW}(E_b) = w E_{SRW}$$

Because aggregation ratio w is less than 1, the total energy cost is necessarily decreased.

To compare the energy cost of the previous routing protocols and to highlight the energy saving due to aggregation, we first compare the energy consumption of the routing protocols without aggregation and then, we consider SWR under the assumption of different aggregation ratio ($w \in [0.2, 1]$). In figure 5, the energy consumption of the given routing protocols is quite different: under our assumptions (small network diameter), SWR consumes less energy than GPSR which is the worst case. By the way, the gain is about 40%. If we consider SWR coupled to aggregation function then, the energy saving increases widely! When $w = 1$, the energy consumption is the same as original SRW protocol due to no aggregation. With the decrease of w, the required packets is gradually smaller, thus the energy dissipation decreases. The energy saving can achieve 80% in SRW when $w = 0.2$. It means appropriate aggregation scheme is more useful and efficient to reduce the energy cost than routing protocols.

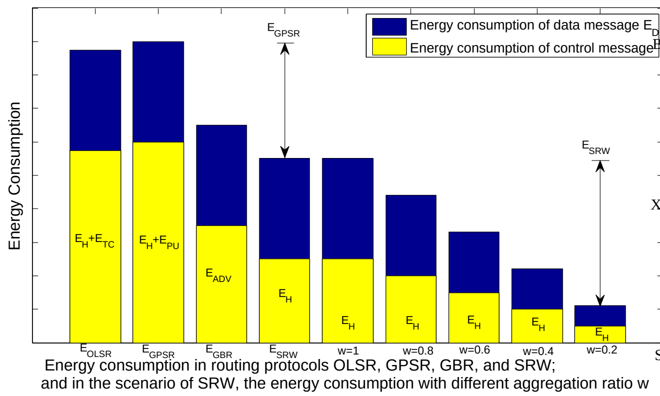

Figure 5: Energy consumption comparison in different routing protocols with and without aggregation

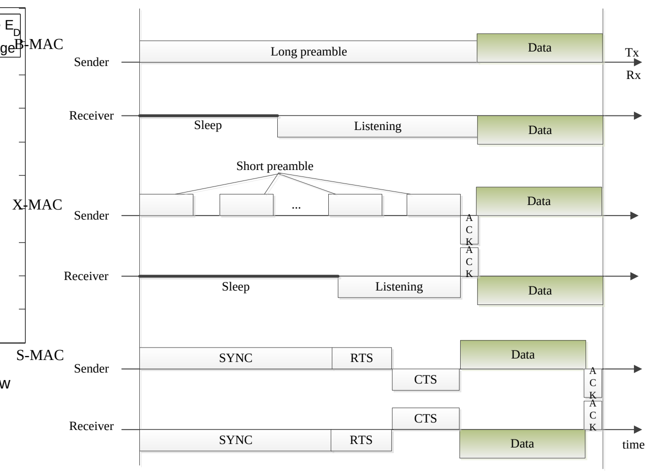

Figure 6: Schematic comparison of the timelines between B-MAC, X-MAC and S-MAC

4 MAC layer-benefits from aggregation

MAC protocols are used to share the medium and avoid collisions between neighbours. Because sensor nodes have low computational, synchronisation capabilities and also memory capacities, MAC protocols face to several limitations. Generally speaking, MAC protocols for WSN usually use a duty cycle mechanism to save energy. Since the receiving, sending and listening energy costs are approximately the same for usual radio chips, the only way to save energy is to turn off the radio (e.g., to switch to sleep mode). The basic idea of duty-cycle MAC protocols consists in a alternatively wake up node and switch to sleep mode. The differences between these protocols are just about the preamble length, the type of configuration in the control packet, and the convective window (BMAC[5], XMAC[7], SMAC[6]).

Figure 6 shows the different MAC mechanisms, which describes the whole process of successful sending-receiving for the 3 previous MAC protocols.

To model the energy consumption for the 3 protocols, we assume Γ is the number of receivers, β is the probability of successful packet reception, others parameters are given in table 1. We consider a data rate of 19.2kbps. More, we assume that the energy consumption for switching between active and sleep modes is negligible in comparison to the proposed energy consumption.

For B-MAC, successfully transmitting a packet consumes E_{BMAC}, which includes preamble, listen, sleep and data:

$$E_{BMAC} = P_{tx}d_p + P_{tx}d_{data} + \beta \cdot \Gamma \cdot (P_s d_s + P_{rx} d_l + P_{rx} d_{data})$$

While X-MAC uses strobe preamble to reduce the energy consumption of the long preamble, which has a expected number of iterations required to determine the preamble frequency. Thus,

$$\begin{aligned} E_{XMAC} &= (P_{tx}d_p + P_{rx}d_{ACK}) * \alpha + P_{tx}d_{data} \\ &\quad + \beta \cdot \Gamma \cdot (P_{rx}d_l + P_s d_s + P_{rx}d_{data} + P_{tx}d_{ACK}) \end{aligned}$$

Before sending packets to the receiver, S-MAC needs to synchronize the neighbors. The energy consumption is E_{SMAC}, which can be formulated as:

$$\begin{aligned} E_{SMAC} &= P_{tx}d_{SYNC} + P_{tx}d_{RTS} + P_{tx}d_{data} + P_{rx}d_{CTS} \\ &\quad + P_{rx}d_{ACk} + \beta \cdot \Gamma \cdot (P_{rx}d_{SYNC} + P_{tx}d_{CTS} \\ &\quad + P_{rx}d_{data} + P_{tx}d_{ACk}) \end{aligned}$$

Using table 1, we are able to compute the energy consumption to send 1 packet for the 3 MAC protocols. We assume the total time for a successful transmission is the same, and the data packet size is 36 bytes. Thus the d_{data} for the 3 protocols is the same, $15ms$. Calculating d_p, d_{ACK} in XMAC is based on the parameters given in [7]. Because we assume the transmission time is the same, if we consider $\alpha = 4$ in XMAC, thus the long preamble is $60ms$. Due to the XMAC mechanism, the listening duration should meet $d_p \leq d_l < 2 \cdot d_p + d_{ACK}$, so given $d_l = 10ms$ and $d_s = 42.8ms$. In BMAC, receivers are randomly wake up, without loss of generality, we use golden ratio to set the value, thus $d_l = 37.08ms$ and $d_s = 22.92ms$. SMAC uses time slots to synchronize and transmit. Due to the parameters in [6], listen interval $75ms$ can be divided to 30 slots (10 for SYNC, 20 slots for data). In addition, assuming ACK duration is the same with XMAC, we can calculate all the parameters for energy consumption.

We assume that 100 packets are transmitted in a given duration, the neighbours' number is 20, and the probability of successful packet reception is 50%(denoted as β). We plot the energy consumption in figure 7. The energy consumption among different protocols are indeed different.

However, if we consider an aggregation scheme with aggregation ratio $w = 0.5$, the energy consumption all decrease 50%, and the benefit for SMAC is significant. Without aggregation, SMAC consumes more than twice than XMAC; after aggregation, the energy cost substantially decrease. That is to say, if there is an efficient aggregation method, there is no need to consider which MAC protocol is better, because any protocol can achieve a better performance coupled to an aggregation scheme.

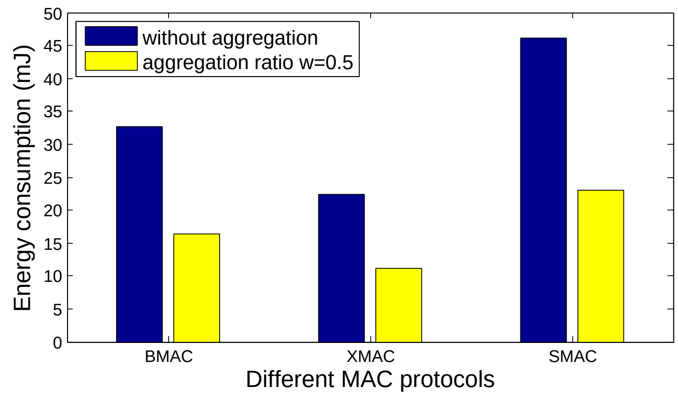

Figure 7: The energy consumption comparison in different MAC protocols with and without aggregation, where aggregation ratio $w = 0.5$

5 The trade-off for data aggregation

As highlighted above, aggregation in WSN can save energy regardless of routing or MAC protocols, and can improve the network capacity. All of the benefits are derived from the nature of aggregation. Data aggregation is based on the temporal or/and spatial correlation to discover the potential relationship between different packets (the correlated packets in general include the redundant information which is no use for the application), and then essentially reduce the redundant information to save both energy and capacity, i.e., reduce the amount of packets, which basically reduce the possibility of collision.

However, as mentioned in section 3, data aggregation may change the packet size. Here, we analyse the relationship between aggregation ratio w, packet size coefficient λ, energy consumption and network capacity.

We consider a WSN network which generates N packets, where the average packet size is p bits, the energy request to transmit 1 bit is E_{bit}. Thus, to transmit N packets, the energy consuming is

$$E = N \cdot p \cdot E_{bit}$$

After aggregation (aggregation ratio is w), the aggregated energy consumption is:

$$E_{agg} = w \cdot N \cdot p(1 + \lambda) \cdot E_{bit}$$

$E_{agg} \leq E$ illustrates that the aggregation method indeed decreases energy consumption, i.e.

$$w \cdot N \cdot p(1 + \lambda) \cdot E_{bit} \leq N \cdot p \cdot E_{bit} \tag{2}$$

$$w \cdot (1 + \lambda) \leq 1 \tag{3}$$

Eq. 3 illustrates the ability of saving energy is $1 - w \cdot (1 + \lambda)$.

Similarly, the network capacity (C_{net}) and maximum link capacity (C_{link}) can be formulated as follow. Without aggregation, the maximum link capacity and network capacity are formulated as:

$$C_{link} = N \cdot p,\ C_{net} = \sum_{i=1}^{N} i \cdot p$$

With aggregation (aggregation ratio is w), the real transmitted packets is $w \cdot N$, and the packets increment is λ, thus the aggregated maximum link capacity and network capacity are:

$$C_{link-agg} = w \cdot N \cdot p \cdot (1 + \lambda)$$

$$C_{net-agg} = \sum_{i=1}^{w \cdot N} i \cdot p \cdot (1 + \lambda)$$

The maximum link capacity can be saved by $N \cdot p \cdot [1 - w \cdot (1 + \lambda)]$.

We plot the Eq. 3 in figure 8, and use colours and areas to describe the potential to save energy and capacity. For the area 5 (warm colors, close to 1), the potential to save energy and capacity is lower; while for the areas 1, 2, 3 (cool colors, close to 0), the potential to save energy and capacity is higher. If the aggregation ratio $w \leq 0.3$, no matter how change the packet size coefficient λ, the energy and capacity savings can reach 50% (see in area 1 and 3); while if $\lambda \leq -0.4$, the value for saving energy and capacity is also greater or equal 50% with aggregation ratio $w \in (0, 1)$ (see in area 2 and 3). When packet size coefficient $\lambda \leq 0.8$ and aggregation ratio $w \leq 0.9$ (area 4), the minimum energy and capacity savings can get to 30%. However, in area 5, the ability for saving energy and capacity is not optimistic (just $\leq 20\%$). Thus, before using aggregation scheme in a real application, it is necessary to trade off the aggregation ratio and packet size coefficient to find the optimal result to save energy and capacity.

From the perspective of energy and capacity, aggregation is the fundamental solution to save energy and capacity, which make the WSN live longer and support more applications. Certainly, we also need to consider the trade off between aggregation ratio and packet size to evaluate an aggregation method.

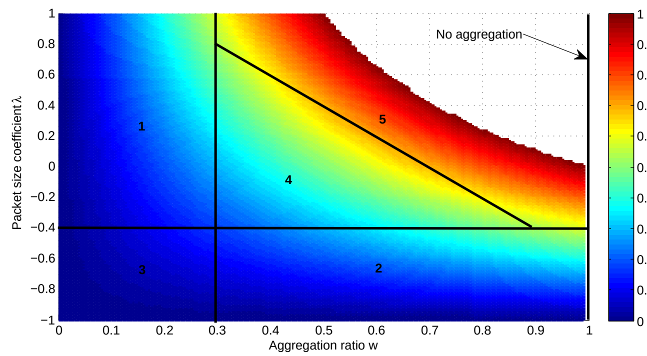

Figure 8: The trade-off between aggregation ratio w and packet size coefficient λ, which show the potential to save energy and capacity.

6 The comparison between compressing and forecasting

Based on the proposed aggregation methods, there are key differences between forecasting aggregation and compressing aggregation. In terms of forecasting, it rely on the time series to forecast, which more based on temporal correlation. While for compressing-based method, it uses the geographic characteristic to compress the data (spatial correlation). Forecasting is based on mathematical model to predict the next value until the model can't be satisfied the accuracy threshold, i.e., if the network is stable enough or there is no environmental affect, there is almost no traffic. Compressing needs parts of sensor regularly reporting, then sink recovers all the data. Forecasting can be applied for only 1 sensor, while compressing is more applicable for large-scale network (the large-scale network is easier to satisfy the requirements of sparsity in CS theory [11]). Regarding the computation, both forecasting and compressing need sensor to simple compute, forecasting needs sensor to compute the parameters, while compressing needs sensor to operate corresponding data.

For the aggregation ratio, suppose there are N nodes in a network, the signal is k-sparse. Sink requires the network report t times in a given duration, i.e., the generated packets is $t \cdot N$, and the probability of the unstable sensors is η (suppose every sensor is independent). Under these assumptions, forecasting aggregates the sensing data with some parameters; at the beginning, every sensor needs to report the parameter, and then just the unstable sensors report; the aggregation ratio is $\frac{N+\eta N(t-1)}{t \cdot N} = \frac{1+\eta(t-1)}{t}$. Compressing needs to recover the original data by the regular reporting, and every time the sensors need $\mathcal{O}(k \log \frac{N}{k})$ measurements out of N (the measurement is usually chosen $3 \cdot k$), thus the aggregation ratio is $\frac{p \cdot \mathcal{O}(k \log \frac{N}{k})}{p \cdot N} \approx \frac{3 \cdot k}{N}$. It shows that compressing is not relevant the report times, while if the report frequency is high and the time series is stable relatively, forecasting should be a better choice.

Table 2 give the difference and the details of the representatives of forecasting and compressing, i.e., A-ARMA and compressive sensing respectively. Due to space constraints, more details can be found in the research report [11].

7 Concluding remarks and perspectives

Data aggregation is a key issue in WSN due to the energy-constrained and bandwidth-constrained. In this work, we illustrate that data aggregation is one of best ways to reduce the energy consuming and improve the network capacity. More, we show that the gain providing by aggregation is always more important than the gain providing by energy-efficient MAC and routing protocols. We analyse the trade-off of aggregation ratio and packet size coefficient, and we provide a comparison between A-ARMA and compressive sensing. In the future, we will investigate performance comparison of state-of-the-art temporal series aggregation and compressive sensing strategy, and more, tend to propose a unifying aggregation method.

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Table 1: Model parameters and value

Parameter	Definition	Value		
		BMAC	XMAC	SMAC
P_{tx}	Power required for transmission	62.5	–	–
P_{rx}	Power required for receive	53.7	–	–
P_s	Power required for sleep	0.02	–	–
d_p	Preamble duration	60	7.8	
d_s	Sleep duration	22.92	42.8	
d_l	Listening duration	37.08	10	
d_{data}	Data transmission duration	15	–	–
d_{ACK}	Acknowledgement duration		7.2	7.2
d_{SYNC}	Synchro. duration			25
d_{RTS}	RTS duration			13.9
d_{CTS}	CTS duration			13.9
α	short preamble repetition required in XMAC		4	
Γ	number of neighbours	20	–	–
β	probability of successful packet reception	50%	–	–

"–" show the value is the same with left column. The units for P_{xx} is mW, and for d_{xx} is ms. We assume in ideal PHY Layer.

Table 2: Comparison between A-ARMA and Compressive Sensing

	A-ARMA	CS
Loss?	not relevance	$\surd$
Correlation	temporal	spatial
Computation on sensor?	$\surd$	$\surd$
Network scale	≥ 1 sensor	large-scale
Methodology	forecasting aggregation	compressing aggregation
Aggregation ratio	$\frac{1+\eta(t-1)}{t}$	$\frac{3 \cdot k}{N}$