Network Coding in Internet of Things

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***Abstract*—Wireless Smart Home Sensor Network (WSHSN) is a home-similar environment, where several wireless sensors can observe the home status and transmit the data streams to the Smart Home Information System (SHIS). Communication in Wireless Sensor Network (WSN) in small living environments faces noise and data transmission speed problems. Especially in the case of employing mobile agents, the WSN restructures dynamically, hence the network performance reduces dramatically. On the one hand, the Internet of Things (IoT) concept includes a broad application of wireless devices, while on the other hand, the WSN throughput decreases significantly by application of more wireless devices. Network coding is a promising technique that can help to broaden the utilization of nodes in WSNs, while network throughput improves by the application of more wireless nodes. In this paper, IoT in WSHSN is modelled as a particular instance of butterfly network and the corresponding network coding based methodology aiming to increase the network throughput is proposed. A case study, supporting the theory of network coding in IoT in small living rooms, is proposed.**

I. Introduction

In smart homes, a number of sensors can observe the human Activities of Daily Living (ADLs) [1]. A Smart Home Information System (SHIS) analyzes the data and through the actuators provides technological life assistance services for its resident. One way to observe the activities is to trace the home resident and the ADL objects such as dishes, spoons, and books which are used to accomplish the ADLs. By modeling the movements of the objects, the SHIS recognizes the activities, predicts the future events and discovers the anomalies.

Wireless communication between the sensors nodes in the home environment is challenging since several wireless transceivers in small rooms transfer wireless data signals together, while the nodes move dynamically. As a result, previously identified noise types form in such this environment [2].

Linear Network Coding (LNC) is a technique which can be used to improve network throughput, efficiency, and scalability, as well as resilience to attacks and eavesdropping. Instead of simply relaying the packets of information they receive, the nodes take several packets and combine them together for transmission. This can be used to attain the maximum possible information flow in a network.

In this paper, we propose the idea of LNC to be applied in WSHSN. We improve the current wireless data transmission rates, and survey the proposed methodology to resolve a real world problem. Our primary contribution is an approach which improves the communication inside WSN elements.

The rest of paper is organized as follows: we present the related works in Section II and in Section III we discuss about network coding in WSNs. In Section IV, we discuss the data streaming in WSN while in Section V we present a network coding based model for wireless IoT. In Section VI, we present a case study, in which the communication between a mobile agent and SHIS is coded, and the delivery of the data streams is improved. In Section VII, we conclude our work.

II. Related work

Recent works on smart home propose wireless communications to substitute the wired connections to take benefit of this technology [4], [5], [6]. In these works, the Wireless Sensor Network (WSN) transmits sensors' observations from the home status to the SHIS. There are some advantages to employing the WSN in the smart home rather than wired home. For example, we may prevent embedding too many sensors and actuators all around the home [2]. Moreover, WSN lets mobile agents running in smart home space [10], [11], and allows implementing the IoT concept in home environment [12], [13].

In [2], four types of noise in the wireless smart home are introduced and analyzed, which are caused by "busy spectrums", "stranger networks", "distances between the WSN nodes" and "the quantity of the transceivers in a small room". Two of the noise types are caused because of using similar spectrums for communications, in the physical layer of Open Systems Interconnection (OSI) communication [14], and two other of the noise types, which are caused by "distance" and "nodes' quantity" factors are in Data-link layer. In order to resolve the physical layer noise, the transceivers are improved in hardware level [15], [16] . A particular noise problem in data-link layer refers to the fact that in wireless networks, we cannot segment the network by the use of media. In other words, with wireless mesh, every node is connected to each other and therefore, the "switch" device, which operates at the data-link layer may not be utilized. As the result, although as soon as Opportunistic Mesh (OPM) wireless devices [15], [16] are turned on, they will connect to each other in OSI physical layer, if we do not manage the network traffic in very early seconds, the data link layer loops will be formed. For the data-link level noise, we proposed a communication algorithm, which manages the sequence of data transmission and an OPM based methodology to resolve the noise matter in the WSHSN [2].

Besides the noise issue, the Received Signal Strength Indicator (RSSI) feature of the WSN signals is used as part of the parameters for navigation of the mobile agent. This feature dependents on the distance of the wireless transceivers [15], and we apply it as feedback indicating the actual position of mobile agent on the graphical model. The mobile agent moves physically in smart home and places the sensors and actuators in target locations at the required time. The proposed model in [2] manages data-link layer noise while it provides the dynamic data-link connections during the transition of the mobile agent.

One distinct objective to employ wireless in the smart home is support of the mobile agents. These agents move in the home environment and may provide customized information about anomalies [17] or anomaly alike situations. In [10], [11], the mobile agents are used as actuators in the smart environment, and particularly in [11] a robot cleans the home environment using wireless technology.

Efficiency in communication with the mobile agent in the smart home environment, while the noise is prevented is the problem, which we will survey in this work. To do this task, we merge the noise-prevented approach proposed in [2], with the network coding technique. The result improves the network throughput rather than the simple noise-prevented approach.

III. Network Coding in WSN

A. Network coding

Network coding is a method for optimizing the flow of digital data in a network by transmitting digital evidence about messages. The “digital evidence” is itself, a composite of two or more messages. When the bits of digital evidence arrive at the destination, the transmitted message is deduced rather than directly reassembled [18], [7], [9]. In a traditional packet-switched network, data flows in defined, discrete “pieces” from the source to the destination like corpuscles in the bloodstream. At the transmitting station, the outgoing message is broken into packets, each of which contains some of the message data intact. The packets do not necessarily travel along the same route, but they all eventually arrive at the same destination, where the receiving node reassembles them into the original message. The main problem with this method is that when the overall network traffic volume is high, bottlenecks are common and wireless noise is formed [2], so the situation results in long delays. Packets tend to bunch up at certain nodes, sometimes more than the nodes’ ability to process them, while other routes and nodes may remain under-utilized.

In network coding, routers and switches are replaced by devices called coders. Instead of directing the packets toward their ultimate destination like blood cells through a system of arteries, the coders transmit metadata in the form of digital evidence about the message along multiple paths simultaneously. Conversely, the metadata arriving from two or more sources may be combined into a single packet. This distribution method can increase the effective capacity of a network by minimizing the number and severity of bottlenecks. The improvement is most pronounced when network traffic volume is near the maximum capacity obtainable with traditional routing. When a receiver has enough digital evidence, it can compute the intended message/ packet. Even if some packets on some of the routes are lost or mutilated, the original message gets through if the received digital evidence is sufficient.

In network coding, the data do not depend only on one transmitted message but also on the contents of other messages that happen to be sharing the route at the time of transmission. The extent of throughput improvement that network coding can provide depends on the network topology and on the frequency and severity of bottlenecks.

In network coding, a message received over the network is not directly taken into account by the receivers; each node interprets the message relying upon on its available knowledge. In this way, the transmitters process the message and send the coded messages over the networks.

B. Butterfly network

Butterfly network is a special case of network coding. Butterfly network represents a better functionality and throughput rather than a router-based version in multi casting, in particular for multimedia contents. In the physical layer, it allows a high rate of data transmission. Furthermore, in wireless networks and satellite communications, it has a famous functionality.

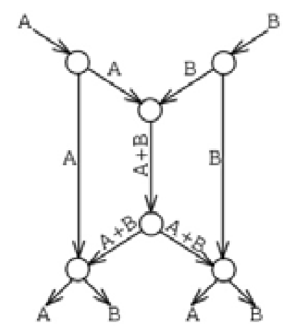

Fig. 1: Butterfly network

As this is illustrated in Fig. 1, in a butterfly network, the messages are coded in some certain nodes and transmitted to the network nodes. The terminal receiver nodes decode the received data and take the final messages simultaneously out. In order to understand better the functionality of butterfly network, we propose a simpler example of the network coding. In this example, the wireless nodes transmit the data (“A” and “B”) in four cycles over a wireless network, as illustrated in Fig. 2.

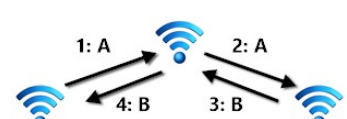

Fig. 2: Simple data transmission over a wireless network

In this example, four cycles for a return message passing are spent; however, by coding the information this rate may be reduced and the idea of network coding may improve $\%25$ the throughput of the network by coding the messages. This will reduce the spent cycles from four to three, as illustrated in Fig. 3.

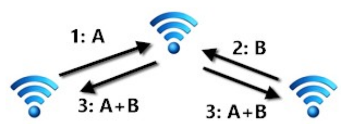

Fig. 3: Coded data transmission over a wireless network

As shown in Fig. 3, by using intermittent transceivers in a wireless network, the messages can be transmitted in fewer steps rather than simple networks. Considering each terminal node knows its previously transmitted data, then it can decode the received data using that key. This technique is helpful in cases that data streams are shared in media. For example, in wireless sensor networks, the data streams might be visible for major parts of the network, but each node may interpret the received data upon its knowledge. As a result, the network flow increases by coding technique. In Fig. 3, at the first step a data byte ("A") is sent to the intermittent wireless transceiver to arrive to the right side device, then "B" is sent from the other side. The intermittent transceiver codes both the data bytes and sends it to all of the nodes in a single step. In this way, within three cycles, each node takes the data byte and decodes it.

C. Wireless sensors network coding

In [19], the network coding theory was first introduced, the "network" is modelled as a graph and network coding is an approach to achieve optimal information flow in the network. In [20], a wireless network coding technique is proposed as a mechanism to reduce the bandwidth requirement of multiple unicast sessions and thus increases the throughput capacity of multi hop wireless networks. In [21], an algorithm to determine dynamically butterfly networks out of several wireless nodes is introduced, while it discusses how the network coding technique improves the packet loss rate in wireless networks. It is also suggested to consider possible butterfly networks between the source and destination nodes, and select the optimum route for data delivery. Due to the wireless nature, the butterfly networks might be formed dynamically; however, the decoding process remains a challenge, while in such dynamic model, the destination nodes require still the decoding key.

IV. Data streaming in WSN

Data streaming in Wireless IoT (WIoT) project is a challenge. In this project, on one side there are sensors which produce the data streams, while on the other side there is main decision-making system (SHIS), so this project characteristically includes several data stream sources but one destination. As a consequence, because several data streams are redirected simultaneously to a unique particular node, the bottleneck problem arises. In [22], it is discussed that in a typical smart home ZigBee WSN, one data byte might

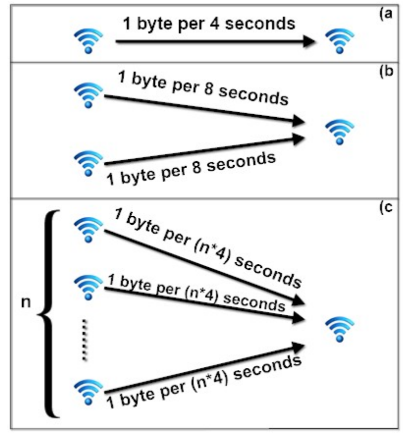

Fig. 4: Uncoded data transmission over a wireless network

normally be transmitted each second; however, with a noise-prevented method it may take up to four seconds. Considering there are two data stream sources, then it will take double time, but even a worse rate might be achieved if more data stream sources transfer data to SHIS, as illustrated in Fig. 4.

As shown in Fig. 4, in a typical uncoded WIoT, the network throughput depends on the number of data sources, which transmit data streams to the central destination.

The main reason for the major delay (normally one second) is that the receiver requires this delay to read wireless signal and put it into its buffer; however, the signal transmitter might serialize the data into bytes and modulate it within a few machine cycles (microseconds). In this way, theoretically, by improving the signal reception rate, we may improve the network throughput.

A. Data streaming speed in WSN

The speed of the data streaming in traditional WSN depends on the number of wireless nodes [2], which source the data streams. Considering $A_{i,j}$ is the j'th data from node i, intended to be sent from a transmitter, and $d_{i,j}$ is the corresponding time of data transmission, then:

$$d_{i,j} \propto A_{i,j} \ \ or \ \ d_{i,j} = \phi \times A_{i,j} \tag{1}$$

For example, in [2] the delay for transmission of a byte to destination is four seconds:

$$d_{i,j} = 4 \times A_{i,j} \tag{2}$$

The effect of network coding is to improve the network throughput or the ϕ coefficient. In the next sections, we will discuss that the ϕ coefficient will be improved in IoT project, if the data streams are coded, and if additional wireless hardware are applied actively in an efficient arrangement (topology).

B. WSN topology

In order to resolve the noise effects in wireless smart home sensor network, some middle level transceivers are predicted in smart home WSN. These transceivers resolve the "distance" and "overhead" effects. The physical order, in which these devices are connected is the topology, and in [2], a multilayer WSN topology is proposed for a wireless smart home, as illustrated in Fig. 5.

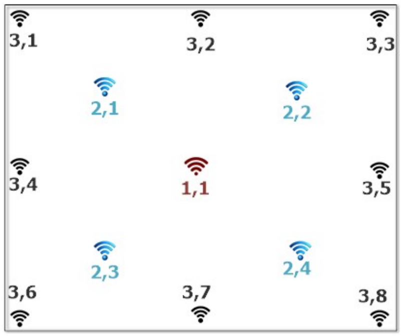

Fig. 5: Proposed multilayer WSN topology for smart home. The black transmitters are the layer three, which are at the farthest layer from the OLIS receiver. The blue transmitters are the layer two, which are at the intermediate distances from the OLIS receiver, and the red one is the main OLIS receiver, layer one.

The topology proposed in Fig. 5 depends on the physical location of the wireless nodes, so the role of each node depends on its actual position. At each moment, only a few devices are active for data transmission and most of the nodes are inactive.

V. Network coding based model for wireless IoT

The wireless IoT is a particular case of wireless butterfly network [21], in which there are multiple data stream sources and a single destination. In a particular application of wireless IoT, which is wireless smart home, various sensors send the wireless data to the SHIS simultaneously.

In a typical WIoT, on the one hand there are several sensors and wireless transmitters, while on the other hand, there is a single wireless receiver node. A particular limitation for WIoT in the smart home is the noise issue [2]. In WIoT, we presume there are n sensors, which transmit data streams to the main computer. The data transmitted from node i at time t is $A_{i,t}$. The delay, for delivery of the corresponding data is $d_{i,t}$.

A. Logical topology

Relying on the physical topology discussed in Fig. 5, we propose a logical multi layer topology for the WIoT. In the first level, there is the main receiver, in the second level there are intermittent transceivers, which code/ decode data streams, and in the last level there is the main receiver node, as illustrated in Fig. 6.

A visual graph [19], representing the proposed topology of the WIoT is shown in Fig. 6. In this three-layer topology, the wireless transceivers are divided into three groups, which are the data stream sources (blue devices), the middle level transceivers (red devices), and the main receiver (the black device). In the proposed model, we presume at each layer, the devices are synchronized and each one sends a data byte after the other. For example the sensor S_2, sends the data byte after sensor S_1 does the job. Similarly in layer 2.

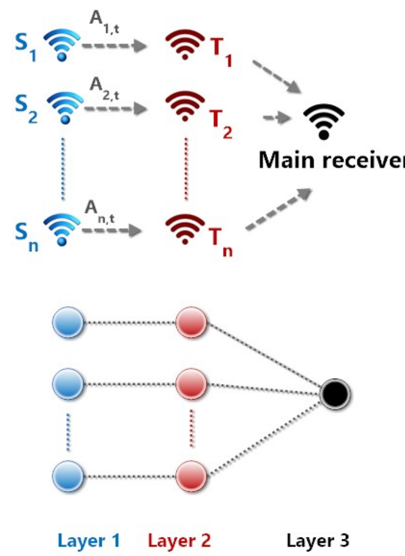

Fig. 6: Graph model for WSN in WSHSN

1) Coding data streams: In order to code the data streams, we require serializing the streams at the transmission points. A particular coder hardware is applied to do it. In the case, where sensors and decoder are at the same location, then the sensors and the decoder layers might be merged together. As this is shown in Fig. 7, a four layer topology for WIoT is proposed, in which the data streams are coded and transmitted toward the main receiver. In particular cases, this model may be reduced to a three layer model.

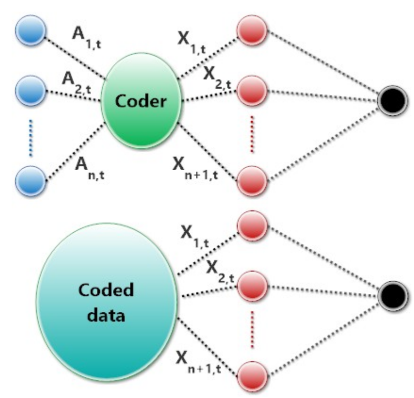

Fig. 7: Graph model for three network coding logical layers

2) Coding and decoding data streams within proposed topology: In order to code the data streams the XOR operator is applied. Presuming there are n wireless transmitters (sensors), then the data of these sensors at time t is: $A_{i,t}|1 \leq i \leq n$. The coded data at time t is: $X_{k,t} = \{A_{i,t}\} + \{XOR(A_{i,t}, A_{j,t})| \; i = 1..n \,, i = 1..n, i \neq j\}$. For example, if there are two nodes in a WSN, then the coded data streams are: $A_{1,t}, A_{2,t}, A_{1,t} \oplus A_{2,t}$.

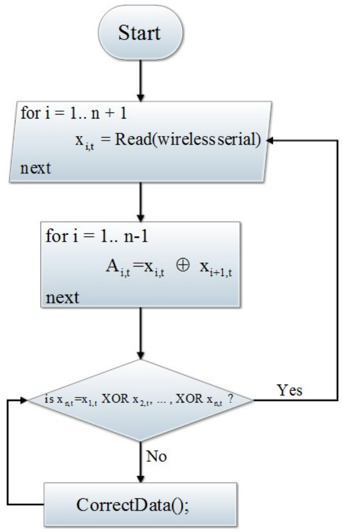

Fig. 8: Decoding algorithm at the main receiver node

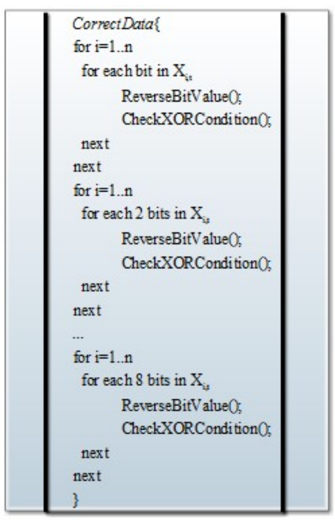

Fig. 9: Proposed correction algorithm for coded WSN

As shown in Fig. 7, the coded data is transmitted to the intermittent devices. These devices read the data sequentially from the coder. In the next step, the data should be decoded at the main receiver. The algorithm in Fig. 8 decodes the data at the receiver.

As shown in Fig. 8, the coded data is received sequentially, and decoded using the XOR operator. The coded data stream included the criteria to check if the data stream is received correctly, as shown in Fig. 9.

VI. Case study: Coding WSN communications in smart home

In this section, we organized an experiment to survey the effect of network coding in smart home wireless communications.

Fig. 10: Smart home mobile agent

A. Experimental setup

In this work we use the OMESH OPM15 devices [8]. The data is transmitted and received in frames at the size of one byte, which is equal to 8 bits. The default baud rate is 9600, and the parity bit is not applied. The property called Request To Send (RTS) / Clear To Send (CTS), which refers to hardware handshaking is disabled. It is set to transmit the next data byte after waiting one second, while the receiver waits also a second before reception of the next data byte, and the frequency band is 2.4 GHz. We also apply a mobile agent, which gets the commands by wireless. The mobile agent is also equipped with a visual sensor, which transfers data with IEEE 802.11 standard. This agent is employed to perform the noise analytics experiments.

We consider the wireless smart home as an instance of WIoT. In this project, there are several wireless transmitters, which transmit data streams simultaneously to the SHIS. In the case we apply a mobile agent in smart home, shown in Fig. 10, which carry the entire sensors. The data streams are created and coded at a single geographical point.

To prevent the effect of "distance" on noise formation, we limited the experiment within the distance of 20 meters. The experience was performed by one, two, three and four data streams. We simulated the effects of more data streams using the proposed network coding approach. The experienced delay in communication is shown in Fig. 11.

As shown in Fig. 11, the delay of network coding approach for data transmission is the most efficient among the existing data streaming methods. The main reason for this effect is to apply more wireless transceivers actively, and use them as the buffers, which let the sensors transmit the data bytes smoothly. In the next step, because, the middle-level transceivers are in close distance to the main receiver, there is no distance noise observed. The coded data is transmitted sequentially, between the corresponding nodes. On the other hand, the proposed correction algorithm prevents requesting resend. In Fig. 12, we are showing the number of required wireless nodes for each approach.

As shown in Fig. 12, the required number of wireless nodes, for the network coding approach is compatible with an unmanaged approach; however, we predict if the number of data

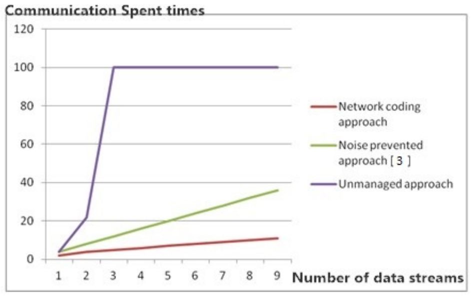

Fig. 11: Data delivery delay for transmitting 10 data data bytes to main receiver

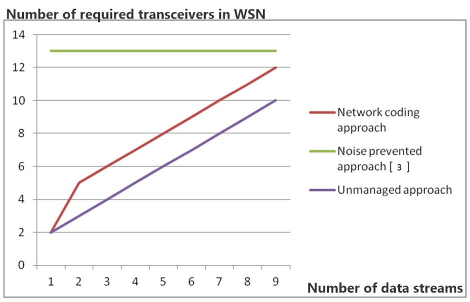

Fig. 12: Number of employed wireless nodes in smart home WSN

streams pass over 13, then a new approach for economizing the network coding technique in smart home will be required.

VII. Conclusion and future works

We proposed network coding technique to be employed in wireless IoT projects, and applied it in smart home environment, where the wireless noise matters. The wireless IoT is a particular case of wireless butterfly network, which has several sourcing nodes and a single receiver. In the proposed case study, we verified the communication between the mobile agent and the smart home information system. In our future works, we will organize noisy contexts to experiment the efficiency of the proposed correction algorithm for wireless network coding project.

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