Traffic-Aware Channel Assignment in Wireless Sensor Networks

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Abstract. Existing frequency assignment efforts in wireless sensor network research focus on balancing available physical frequencies among neighboring nodes, without paying attention to the fact that different nodes have different traffic volumes. Ignoring the different traffic requirements in different nodes in frequency assignment design leads to poor MAC performance. Therefore, in this paper, we are motivated to propose traffic-aware frequency assignment, which considers nodes' traffic volumes when making frequency decisions. We incorporate our traffic-aware frequency assignment design into an existing multi-channel MAC, and compare the performance with two conventional frequency assignment schemes. Our performance evaluation demonstrates that traffic-aware channel assignment can greatly improve multi-channel MAC performance. Our traffic-aware assignment scheme greatly enhances the packet delivery ratio and system throughput, while reducing channel access delay and energy consumption.

1 Introduction

As an emerging technology, Wireless Sensor Networks (WSNs) have a wide range of potential applications, including environmental monitoring, smart buildings, medical care, and many other industry and military applications. A large number of protocols have been proposed for the MAC, routing and transport layers. However with a single channel, WSNs cannot provide reliable and timely communication with high data rate requirements because of radio collisions and limited bandwidth. For example, in the "Ears on the ground" project [7], the network cannot transmit multiple acoustic streams to the sink. On the other hand, current WSN hardware such as Micaz [3] and Telos [12] which use the CC2420 radio [2], already provide multiple frequencies. So it is imperative to design multi-channel based communication protocols in WSNs to improve network throughput and provide reliable and timely communication services.

Typically, multi-channel protocols consists of two major components, channel assignment and media access control. A good channel assignment method can effectively reduce radio interference among concurrent transmissions, mitigate packet congestion within a single channel, and make media access control easier. It is the key performance factor for multi-channel communication. In the state of the art, many channel assignment schemes are proposed in wireless ad hoc networks and mesh networks, but they cannot be directly applied to sensor networks. This is because nodes in ad hoc and mesh networks are usually equipped with more powerful radios or even multiple radios, each of which can use one unique channel. Conversely, a sensor node such as Micaz, with only a single half-duplex radio, can only use one channel at one time [18]. Recently, some multi-channel protocols are proposed for WSNs. Most of them offer some *static* solutions to channel allocations, aiming to minimize potential interference among nodes. Since topologies of sensor networks are quite static, such static solutions can be executed in the deployment time, or infrequently during runtime, and they help MAC protocols improve communication performance on average.

In this paper, we focus on channel assignment problems in sensor networks. We believe that existing static approaches for channel assignment are insufficient because of two reasons. First, they try to reduce potential interference with the assumption that all nodes have the same amount of traffic to carry simultaneously. This assumption is not true for most WSNs, where only a fraction of nodes need to transmit packets at any time. Second, even though a specific sensor network is deployed statically, the traffic volume and pattern can vary significantly both across the deployment area and across time. For example, a military intrusion detection sensor network [5] may have a regular and low speed traffic involving a few nodes when no intrusion is occurring, but may experience a large burst of traffic affecting a lot of nodes when enemy tanks are detected. Such traffic variability can change the interference pattern, and hence a multi-channel MAC with static channel assignment will severely suffer in terms of performance.

To improve current channel assignment solutions, we develop and systematically study the notion of *traffic-aware* channel assignment for WSNs. We start by considering a setting where perfect information about current and future traffic is available. Then we propose a new channel assignment scheme which exploits this traffic information to minimize interference occurring with real traffic. We compare this scheme with two typical static channel assignment schemes by simulation, and results show that being *traffic-aware* can substantially improve the performance of channel assignment. This baseline analysis helps establish the potential benefits of traffic-aware channel assignment algorithms.

In the future, we are going to study how to efficiently deal with the traffic variability during system runtime. Some questions are: how to predict the future traffic? When traffic varies and the prediction fails, how can we change channel assignment dynamically? Of course, solutions of these questions must not bring too much overhead, and must converge to a stable assignment in limited time.

2 Related Work

In general wireless networks, frequency diversity has been studied for years and a significant number of multi-frequency MAC protocols have been proposed. However, the purposed protocols are a poor fit for wireless sensor networks due to the restricted sensornet hardware, its limited bandwidth, and the small WSN MAC layer packet size [18]. For example, some protocols [13] [14] are designed for frequency hopping spread spectrum (FHSS) wireless cards, and one protocol [4] assumes the busy-tone functionality on the hardware. In other protocols [11] [15] [10] [1], the hardware is assumed to have the ability to listen to multiple frequencies at the same time. In addition to hardware restrictions, the network bandwidth in WSNs is very limited and the MAC layer packet size is very small, 30$\sim$50 bytes, compared to 512$+$ bytes used in general wireless networks. Different from all above solutions, this paper addresses how to use multiple channels efficiently in the context of wireless sensor networks, where each node only has one radio and can only use one channel at one time.

Some multi-channel MAC layer protocols have been proposed to improve network performance in WSNs. These protocols typically assign different channels to two hop neighbors to avoid potential interference, and also propose sophisticated MAC schemes to coordinate channel switching and transmissions among nodes. Simulation results show that they can significantly improve network throughput over MAC protocols using a single channel. Clearly, the most important problem of these protocols is how to assign different channels to nodes. Most protocols use "static" channel assignment, where the channel selection process are executed at the beginning of system deployment, or very infrequently during runtime. For example, MMSN [18] has a frequency assignment component, which provides four available frequency assignment strategies. Users can select any of these methods to evenly assign different channels among two-hop neighbors. TMCP [16] proposes a tree-based channel assignment scheme. The idea of the TMCP protocol is to first partition the whole network into multiple vertex-disjoint subtrees all rooted at the base station and allocate different channels to each subtree, and then forward each flow only along its corresponding subtree. One common problem of these two protocols is that they use no traffic information to assign frequencies. Instead, both protocols assume that traffic is evenly distributed on each node. However, this is often not true in reality, where traffic patterns change significantly during runtime and some nodes or segments of the network may have more traffic than others. With this uneven traffic distribution, frequency assignment schemes of both protocols may fail to provide good performance because they may waste channels on nodes who have no traffic but assign too few channels to nodes who have heavy traffic. Instead, our traffic-aware channel assignment scheme exploits traffic information to achieve better assignment solutions and can dynamically adapt to traffic pattern changes during runtime.

Recently, a multi-channel protocol [9] is proposed which also has the capability of dynamically changing the radio frequency. However, their approach is based on local decision, where each node makes its own decision to switch channels. Our traffic-aware method collects traffic information from two-hop neighbors, and uses a specific algorithm to assign channels among two-hop neighbors which results in more efficient channel usage.

3 Channel Assignment Scheme

In this section, we first explain two typical static channel assignment schemes [18]: even selection and eavesdropping, and then propose a new *traffic-aware* channel assignment approach, which uses traffic information to achieve load balance among channels and effectively reduces runtime system interference. Lastly, we compare our *traffic-aware* channel assignment with the two existing approaches through simulation evaluation.

3.1 Static Channel Assignment

In channel assignment, each node is assigned a physical channel for data reception. The assigned channel is broadcast to its neighbors, so that each node knows what channel to use to transmit unicast packets to each of its neighbors. In order to reduce communication interference and hence reduce hidden terminal problems [6], static solutions evenly assign available channels to nodes within two communication hops. In WSNs, such static channel assignments are considered to either be done once at the beginning of the system deployment, or it can be done very infrequently for adaptation to system aging. In this subsection, we describe two channel assignment schemes proposed in [18]: even selection and eavesdropping.

Even Selection In even selection assignment, nodes first exchange their IDs among two communication hops [17], so that each node knows its two-hop neighbors' IDs. To achieve this, each node first beacons its node ID to neighbors, so that each node knows its neighbors' IDs within one communication hop. Then, each node beacons again, broadcasting all neighbors' IDs it has collected during the previous beacon round. Therefore, after two rounds of beacons, all nodes get their neighbors' IDs within two communication hops.

After the two rounds of beacons, nodes begin to choose data receiving frequencies (or channels) in the increasing order of their ID values. If a node has the smallest ID among its two communication hops, it chooses a channel first and it chooses the smallest channel among available channels. The node then beacons its channel choice within two hops. If a node's ID is not the smallest among two hops, it waits for channel decisions from other nodes within two hops that have smaller IDs. When decisions from all those nodes are made and are also received, the node chooses the smallest available (not chosen by any of its two-hop neighbors) channel. If all channels have been chosen by at least one two-hop neighbor, it randomly chooses one of the least chosen channels. After picking a channel, the node broadcasts its choice within two hops. We call this scheme *even selection*, which makes an even allocation of available frequencies to all nodes within any two communication hops.

When the number of frequencies is at least as large as the two-hop node number, *even selection* guarantees to assign different frequencies to different nodes within any two-hop neighborhood. When the number of frequencies is small, *even selection* allows two-hop neighbors evenly share the available frequencies.

Eavesdropping We observe that although *even selection* results in even sharing of available frequencies among two-hop neighbors, it requires a number of two-hop broadcasts. To reduce the communication overhead, a lightweight eavesdropping scheme is also proposed in [18]. In eavesdropping, each node takes a random backoff before it broadcasts its physical channel decision. Each node also records overheard physical channel choices during the backoff period. After the random backoff, a node randomly chooses one of the least chosen frequencies for data reception. Compared with *even selection*, *eavesdropping* requires less communication overhead, but leads to more potential conflicts since it only collects information within one hop rather than two hops for channel decisions.

3.2 Traffic-Aware Channel Assignment

In this section, we introduce a traffic-aware channel assignment scheme. Here, the term "traffic aware" means that nodes have knowledge about future traffic. More precisely, nodes know their reception data rates of the future. Now, we assume that the traffic data rate does not change, while in the future we intend to discuss dynamic traffic. One practical problem is the dissemination of dymamic traffic information to nodes. One practical way is that at regular intervals, nodes calculate the reception data rate, and use it to determine channel assignment. Also, considering that sensor networks are used to periodically collect environment data in most scenarios, upper layers can pass such application information to the channel assignment component, and then the reception data rate can be inferred from those collection tasks' settings.

Now, every node is assigned a traffic weight, which corresponds to its future reception data rate. The problem is to assign the right channel to each node, aiming to minimize the maximum load of any channels within the two-hop neighborhood of any node. Here, we choose this goal because the more load one channel takes, the more likely radio collisions occur in this channel. Also, the channel load affects the throughput and the latency of communication. We also find that this problem is very similar to the load balancing job scheduling problem, where each channel can be viewed as one machine, and the traffic weight of each node corresponds to the processing time of each job. The difference between these two problems is that in our channel assignment, we require the load balance within any two-hop neighborhood, but the job scheduling problem only asks the load balance for one group of machines. If the diameter of this network is two hops, our traffic-aware channel assignment problem is the exact same problem with the load balancing job scheduling problem. Since the job scheduling problem is NP-hard, it is clear that our traffic-aware channel assignment problem is also NP-hard.

In the light of NP-completeness, there is no polynomial time exact algorithm which can always find the optimal assignment. Next, we propose a greedy traffic-aware channel assignment scheme.

First, nodes exchange their IDs and their traffic weights among two communication hops, so that each node knows its two-hop neighbors' IDs and traffic weights. After nodes collect traffic information of all neighbors within two hops, they make channel decisions in the decreasing order of their traffic weight, with the smallest node ID used as a tie breaker. If a node has the greatest traffic weight among its two communication hops, it chooses the channel with the least load among available channels, and then beacons the channel choice within two hops. After receiving this beacon, nodes update the load of the corresponding channel. If a node's traffic weight is not the greatest one among two hops, it waits for channel decisions from other nodes within two hops that have greater weight. A node also waits for all nodes with equal weight but lower node ID to make decisions first. After decisions from all nodes with greater weight or equal weight but lower node ID are received, a node chooses the channel with the least load. Since nodes choose channels in sequence by decreasing weight with a node ID tiebreaker, our assignment algorithm will always converge for any set of nodes and traffic weights.

This traffic-aware channel assignment scheme uses a similar concept as that of the Longest Processing Time algorithm (LPT) for the job scheduling problem. It is proven that the approximation ratio of the LPT algorithm is $\frac{4}{3} - \frac{1}{m}$, where m is the number of machines. However, we have not yet calculated the approximation ratio for our traffic-aware channel assignment algorithm and leave it to future work. Now, we only know that $\frac{4}{3} - \frac{1}{m}$ is a lower bound for our algorithm. In terms of overhead, our algorithm has similar overhead as the even selection assignment scheme, except adding several bytes in beacon messages to exchange the traffic weight.

4 Performance Evaluation

In this section, we compare the performance of two static channel assignment schemes and the new traffic-aware assignment. For these three approaches, we use the same medium access control method, which is designed in [19]. Also, we assume that every node has perfect knowledge about its future reception data rate.

For this performance evaluation, two groups of experiments are designed. In the first group, different system loads are used, and in the second group of experiments, the number of available channels is varied.

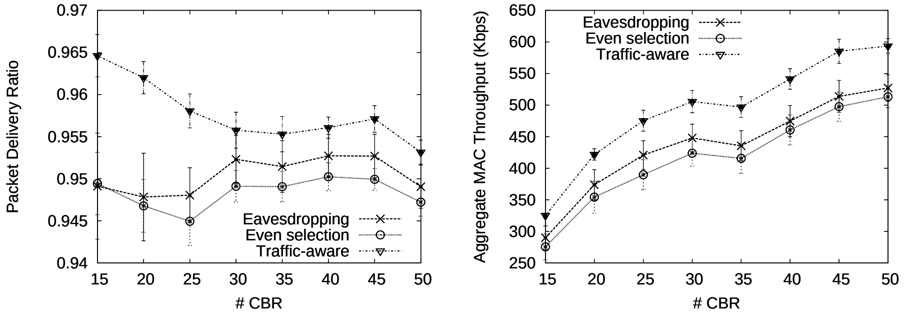
Table 1. Simulation Configuration

TERRAIN	(200m×200m) Square
Node Number	289
Node Placement	Uniform
Application	Many-to-Many CBR Streams
Payload Size	32 Bytes
Routing Layer	GF
MAC Layer	CSMA/MMSN
Radio Layer	RADIO-ACCNOISE
Radio Bandwidth	250 Kbps
Radio Range	20m∼45m

For all the two groups of experiments, four performance metrics are adopted: aggregate MAC throughput, packet delivery ratio, channel access delay, and energy consumption per successfully delivered data byte. The packet delivery ratio is calculated as the ratio of the total number of data packets successfully delivered by the MAC layer over the total number of data packets the network layer requests the MAC to transmit. The aggregate MAC throughput measures the performance gain and is calculated as the total amount of useful data successfully delivered through the MAC layer in the system per unit time. The channel access delay measures the time delay a data packet from the network layer waits for the channel before it gets sent out. The energy consumption per byte is the system wide energy consumed for successfully delivering one byte of user data.

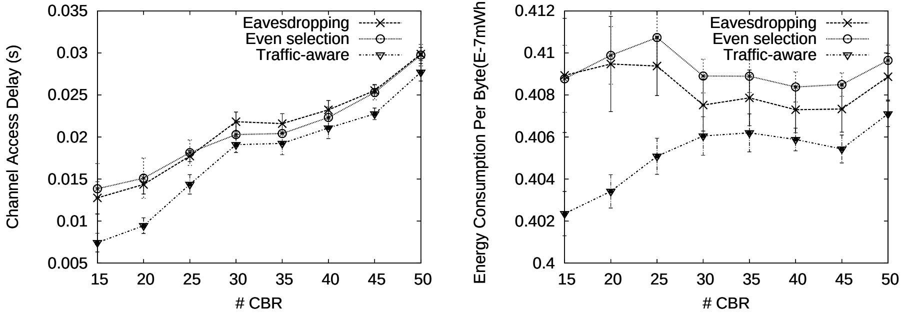
During all the experiments, the Geographic Forwarding (GF) [8] routing protocol is used and the simulation is configured according to the settings in Table 1. For each data value we present in the results, we also give its 90% confidence interval.

4.1 Performance Evaluation with Different System Loads



(a) Packet Delivery Ratio in MAC

(b) Aggregate Throughput in MAC



(c) Average Channel Access Delay

(d) Energy Consumption Per Delivered Data Byte

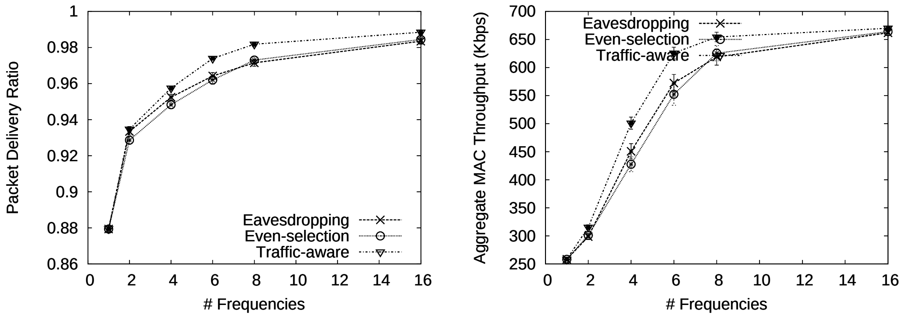
Fig. 1. Performance Evaluation with Different System Loads

In the first group of experiments, we explore traffic-aware assignment's performance when different system loads are used, which are generated by different numbers of CBR streams. In the experiments, the node density is set to 38 and the number of available channels is 5.

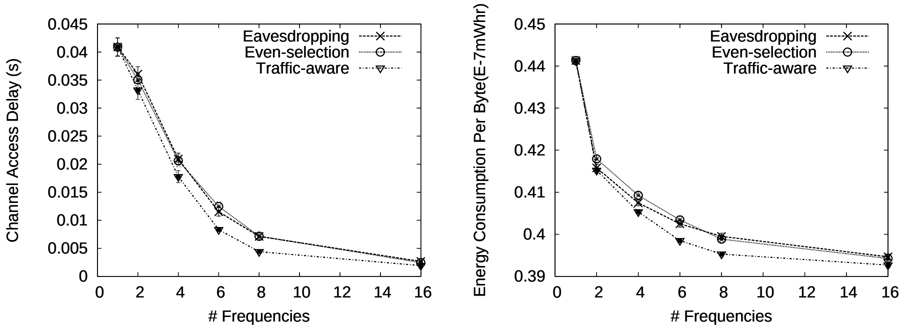
As Figure 1 shows, for all the system loads we configure from 15 CBR streams to 50 CBR streams, it is observed that traffic-aware assignment always exhibits better performance than static schemes in all performance metrics in all scenarios. For example, as shown in Figure 1, comparing with the best static scheme, traffic-aware scheme achieves on average 13.5% higher aggregate throughput as shown in (b). It is clear that traffic-aware channel assignment effectively reduces radio interference, and by keeping the load balance among channels it mitigates packet congestion within channels and leads to high throughput and lower latency.

Another interesting trend is that when the system load is light or heavy, the traffic-aware assignment outperforms static schemes with a large gap, but when the system load is medium, like 30 streams, the performance of the traffic-aware scheme is very close to static schemes. One possible reason is that with such medium loads, most nodes have similar traffic weights, which also allows static schemes to perform well.

4.2 Performance Evaluation with Different Numbers of Channels



(a) Packet Delivery Ratio in MAC (b) Aggregate Throughput in MAC



(c) Average Channel Access Delay (d) Energy Consumption Per Delivered Data Byte

Fig. 2. Performance Evaluation with Different numbers of channels

In many deployed sensor network systems, the number of available channels may vary. For example, in an indoor scenario, the interference from WiFi networks may decrease the number of available channels that sensor networks can use. So, in the second group of experiments, we evaluate the performance of channel assignment schemes when different numbers of channels are utilized. The number is increased from 1 to 16, and a many-to-many traffic pattern is used that consists of 50 CBR streams.

Once again, the experimental results confirm that traffic-aware assignment always achieves a higher performance than static schemes, which can be observed in Figure 2 (a)∼(d). The corresponding reasons can be found in the first groups of experiments and are not repeated here.

It is shown that when the channel number is small, for example 1 or 2, the performance of all schemes is very close. When we have many channels, such as 16, the performance is also close. On the other side, when the channel number is medium, like 4, 6, 8, the traffic-aware scheme obviously outperforms others. We believe that in practice, one sensor network may co-exist with other sensor networks or WiFi networks, and in most cases, the number of available channels is around such medium values.

5 Conclusion

Existing frequency assignment efforts in wireless sensor network research focus on assigning available physical frequencies as evenly as possible to neighboring nodes, ignoring the runtime condition that different nodes have different traffic requirements. Failure to address different traffic volumes during frequency assignment design leads to poor MAC performance, which has been identified and demonstrated in our performance evaluation. In this paper, we propose a traffic-aware frequency assignment design that actually considers different traffic requirements from neighboring nodes while making frequency decisions. The traffic-aware frequency assignment is incorporated into the existing MMSN MAC and compared with two conventional frequency assignment methods: even selection and eavesdropping. Our simulation evaluation demonstrates that the traffic-aware channel assignment greatly improves multi-channel MAC performance: it significantly enhances the the packet delivery ratio and throughput, while at the same time reducing channel access delay and energy consumption.

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