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***Abstract*—We propose a new energy efficient network structure for maintaining synchronization in channel access methods based on Synchronous Preamble Sampling. Our scheme limits the number of synchronization messages and increases network capacity through the use of multiple non-interfering *virtual channels*. It consists in constructing independent clusters based on the Weakly Connected Dominating Set (WCDS) so that they can use different virtual channels and only need to maintain internal synchronization, while still offering global connectivity. We define a distributed and self-stabilizing algorithm for constructing and maintaining the clusters. Our simulation results show that the proposed scheme has comparable energy consumption to Scheduled Channel Polling, but results in better network capacity. Moreover, it achieves better energy savings and network capacity than the recently proposed Crankshaft access method.**

I. Introduction

Most of the research on wireless sensor networks has focused on energy saving. As radio communications are responsible for most energy consumption, many proposals aim at optimizing the MAC layer and its use of radio transmissions. Preamble Sampling [1], also referred to as Low Power Listening [2], is the key technique for reducing *idle listening* in sensor networks. Idle listening is undesirable, because nodes consume energy while listening to an idle channel [3]. It mainly occurs in contention-based access methods in which nodes listen to the channel for long periods of time, because they do not know the exact instant at which other nodes may send a frame. In preamble sampling, a node sends a *preamble* before each data frame, while nodes wake up each *check interval* to sample the channel for the preamble and receive a frame—if the preamble lasts for at least one check interval, the receiver surely wakes up during the preamble transmission. After sensing the preamble, potential receivers must stay awake to receive a data frame.

In Synchronous Preamble Sampling, nodes coordinate their wake-up instants to have a common schedule—they sleep during the same interval to save energy and then wake up to exchange data frames [4]. To maintain the common schedule, each node needs to periodically broadcast a SYNC control frame to make up for clock drifts.

Although this method drastically reduces energy consumption by minimizing idle listening, it presents some shortcomings. First of all, SYNC signaling frames represent significant overhead that increases energy consumption. Moreover, when nodes wake up, they synchronously contend for the radio channel, which results in collisions that waste bandwidth and energy. Finally, the overall network capacity is lower, because all transmissions happen in the same common wake-up slot, while nodes sleep the rest of the time.

To overcome these shortcomings, we propose to structure the network in a way that limits the number of synchronization messages and increases network capacity through the use of multiple *virtual channels*. We construct independent clusters that maintain their own synchronization and use their own virtual channels while keeping global network connectivity. We define a virtual channel as a means for communication in a group of nodes through the use of any combination of time (TDMA), frequency (FDMA), or code (CDMA) multiplexing. For instance, Wavenis products [5] combine different time slots (or schedules) and specific frequency hopping sequences per time slot to define multiple virtual channels. Two nodes that use different virtual channels cannot directly communicate, but can operate in parallel, which increases the overall network capacity.

To reduce the number of exchanged SYNC frames while maintaining the network connected, we structure it according to a Weakly Connected Dominating Set (WCDS) [6]. A WCDS is composed of independent clusters that can use different virtual channels for internal communication, which only requires maintaining synchronization inside one cluster. In this way, all transmissions benefit from Synchronous Preamble Sampling because of the WCDS structure property. Thus, only a subset of nodes needs to transmit SYNC frames instead of all nodes in traditional Synchronous Preamble Sampling.

The contribution of this paper is twofold:

- we propose a new network structure based on a WCDS to limit energy waste for maintaining synchronization while increasing network capacity through the use of multiple non-interfering virtual channels;
- we present a simple distributed self-stabilizing algorithm for a WCDS that leads to two variants: full-WCDS bridged-WCDS;

II. Related Work

WiseMAC [7] is among the first implementations of synchronous preamble sampling. Each node maintains its own schedule and piggybacks synchronization information in its `ack` frames. WiseMAC improves network capacity by setting up multiple virtual channels, but long preambles are required to transmit broadcast frames or when synchronization is lost between source and destination nodes.

Scheduled Channel Polling (SCP) [4] has shown that explicit transmissions of SYNC frames do not reduce the overall energy savings, because the benefits of using short preambles finally lead to more energy savings. SCP maintains the common schedule throughout the network to save broadcast communications the need of using long preambles. With such a design, SCP trades capacity for energy savings, because contention drastically increases when nodes use the same virtual channel (i.e. the same wake-up schedule).

Crankshaft [8] reduces contention by using preamble sampling on top of a TDMA scheme. TDMA slots correspond to virtual channels: to send a frame a node uses the slot of the receiver to transmit its data frame. If the receiver does not detect any transmission, it can immediately go back to sleep. Since each node has its own virtual channel, Crankshaft increases network capacity.

Y-MAC [9] uses a similar approach, but multiplies virtual channels when traffic increases. Initially, it assigns slots to each receiver like Crankshaft, but a node can negotiate additional virtual channels for each of its neighboring senders. In this way, Y-MAC adapts to traffic conditions: the network uses more virtual channels when more frames need to be forwarded. Wavenis [5] adopts a similar approach, but adds a combination of slow and fast frequency hopping between physical channels to further increase robustness to interference.

Although Crankshaft, Y-MAC, and Wavenis increase capacity by reducing contention through the use of multiple virtual channels, they suffer from an additional overhead related to the broadcast channel—under these access methods, nodes need to listen to the additional broadcast channel for receiving broadcast communications. Therefore, the energy drained in periodically checking the channel is doubled, which results in an important energy waste especially in low traffic data networks.

SPAN [10] proposed to elect a forwarding backbone by selecting a Connected Dominating Set. This structure is more designed for traffic forwarding—SPAN operates above a channel access method. We focus on reducing energy consumption due to synchronization while enabling multichannel operation for increasing network capacity.

III. Energy Cost for Synchronous Preamble Sampling

The power drained in Synchronous Preamble Sampling consists of the power consumed during channel sampling and the power spent on sending and receiving SYNC frames. Both of these operations are periodic. Channel sampling is performed every Check Interval T_{CI} and SYNC frames are transmitted every Synchronization Interval T_{SI}.

We call E_{sampling} the energy drained during a channel sampling operation. Therefore, the mean power drained in channel sampling is:

$$\mathcal{P}_{\text{samp}} = \frac{E_{\text{sampling}}}{T_{\text{CI}}} \quad (1)$$

The cost of transmitting a frame (SYNC or another frame) depends on the accuracy of synchronization between the transmitter and the receiver. As synchronization is not perfect, the transmitter does not know the exact wake-up time of the receiver. Therefore, the transmitter sends a short preamble before the data frame to make sure that the receiver finds the channel busy when it wakes up to sample the channel. When the receiver finds the channel busy, it keeps listening until it receives the data frame. The length of the short preamble T_{preamble} depends on the clock drift θ and the periodicity of maintaining synchronization (T_{SI}) [7]:

$$T_{\text{preamble}} = 4\theta T_{\text{SI}} \quad (2)$$

Note that the length of the preamble does not need to be larger than T_{CI}, because each node wakes up every T_{CI} to check for transmissions.

When exchanging SYNC frames, a node may be a *reference* and/or *follower*. A node is said to be a reference, if it transmits its clock to its neighbors and is said to be a follower, if it adjusts its clock to the time received from a reference. Nodes with synchronized clocks can use short preambles for their transmissions thereby avoiding the use of costly long preambles. In this case, we will refer to the link between the nodes as *synchronized*.

The mean power drained by a reference (resp. a follower) node $\mathcal{P}_{\text{ref}}$ (resp. $\mathcal{P}_{\text{foll}}$) corresponds to cost of transmitting (resp. receiving) a SYNC frame, which is equal to:

$$\mathcal{P}_{\text{ref}} = \left(\frac{T_{\text{preamble}} + T_{\text{SYNC}}}{T_{\text{SI}}}\right) P_{\text{tx}} = \left(4\theta + \frac{T_{\text{SYNC}}}{T_{\text{SI}}}\right) P_{\text{tx}} \quad (3)$$

$$\mathcal{P}_{\text{foll}} = \left(\frac{\frac{T_{\text{preamble}}}{2} + T_{\text{SYNC}}}{T_{\text{SI}}}\right) P_{\text{rx}} = \left(2\theta + \frac{T_{\text{SYNC}}}{T_{\text{SI}}}\right) P_{\text{rx}} \quad (4)$$

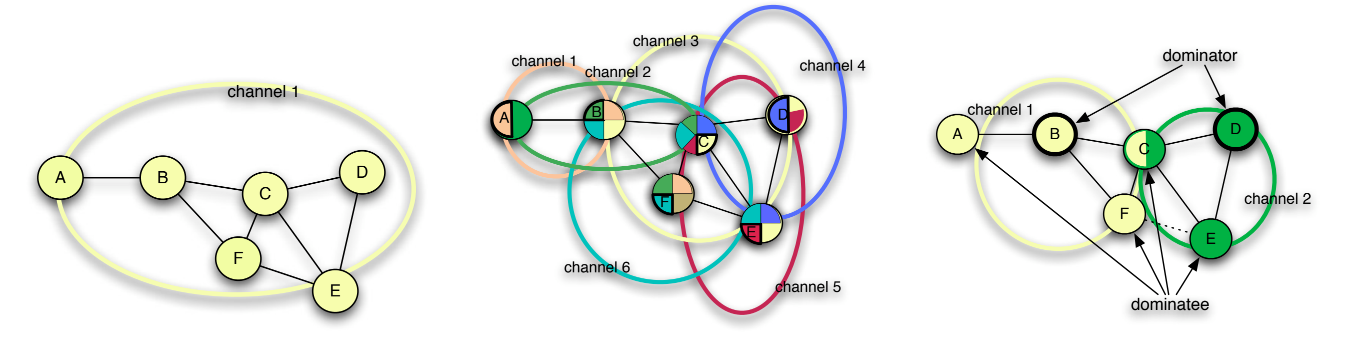
where P_{tx} (resp. P_{rx}) is the power drained in the transmit (resp. receive) mode and T_{SYNC} is the transmission time of a SYNC frame. Note that the mean preamble reception time in Eq. 4 is a half of the preamble, because the receiver may wake up at any time between the beginning and the end of the preamble.

IV. Network Structure for Maintaining Synchronization

Our objective is to minimize the cost of maintaining synchronization. To achieve this, we want to reduce the number of reference nodes, but in a way that preserves connectivity: there exists a path between any two nodes in the network over synchronized links. Another objective is to increase the overall network capacity that we can achieve by using multiple virtual channels.

A. Preliminaries and Definitions

Limiting the number of reference nodes while maintaining network connectivity relates to the problem of constructing a Weakly Connected Dominating Set (WCDS) so we introduce this notion more formally. We represent a sensor network as an undirected graph $G = (V, E)$, where V is the set of nodes and $E \subseteq V^2$ the set of edges. An edge (u, v) belongs to E if u can communicate with v. The set of neighbors of a node



(a) SCP (b) Crankshaft (c) WCDS

Fig. 1. Synchronization Maintenance.

u is $N(u)$. Formally, the WCDS we want to find satisfies the following conditions:

$$\forall d \notin \text{WCDS},\ \exists d' \in \text{WCDS} | d' \in N(d) \tag{5}$$

$$G(V, E') \text{ connected} | E \supseteq E' = \{(u, v)\}, u \in \text{WCDS}, v \in V \tag{6}$$

The nodes belonging to the WCDS set are called *dominators* and the other ones *dominatees*. From the synchronization point of view, dominators are references while dominatees are followers. All links between dominators and dominatees are synchronized—the nodes can use short preambles: a dominatee uses for its receptions/transmissions the virtual channel established by the dominator. Moreover, a path that uses only the links between dominators and dominatees exists in the network between any pair of nodes; it is one of the main property of a WCDS. Thus, the network can exclusively use synchronized links to forward traffic.

A dominator and the set of its neighboring dominatees form a *cluster*. The dominator is its *clusterhead*: it defines the virtual channel used all nodes in the cluster and maintains synchronization with periodical SYNC frames. A dominatee that belongs to several clusters can act as a *bridge* to forward traffic from one clusterhead to another by switching to different virtual channels.

B. Motivating Example

Let us consider the cost of running Synchronous Preamble Sampling under different access methods. Consider the network depicted in Figure 1 and let us focus on the energy drained by node C as an example.

In SCP, each node transmits a SYNC frame to propagate the same schedule throughout the entire network. As a consequence, each node receives as many SYNC frames as the number of its neighbors. In addition, each node needs to sample the channel to check for incoming frames. Thus, node C consumes a mean power equal to $\mathcal{P}_{\text{ref}} + \mathcal{P}_{\text{samp}} + 4\mathcal{P}_{\text{foll}}$.

In Crankshaft, each node consumes similar energy as in SCP to maintain synchronization and to check for incoming unicast traffic. As broadcast communications are performed on another virtual channel, each node needs to sample two channels. Thus, node C consumes a mean power equal to $\mathcal{P}_{\text{ref}} + 2\mathcal{P}_{\text{samp}} + 4\mathcal{P}_{\text{foll}}$.

In our WCDS-based structure, nodes B and D are dominators and act as references. Node C acts as a bridge between the clusters of B and D: it listens to both virtual channels (channel 1 maintained by B and channel 2 maintained by D). Node C does not transmit SYNC frames, so it consumes a mean power equal to $2 * (\mathcal{P}_{\text{foll}} + \mathcal{P}_{\text{samp}})$. Compared to the other schemes, the power spent on maintaining synchronization is reduced.

C. Distributed Construction of WCDS

Several centralized algorithms exist for constructing a WCDS [11], [12]. We provide here a distributed version that takes into account node failures and frame losses.

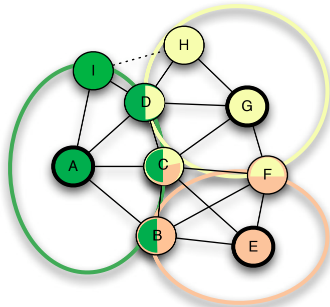
We define three node states: *idle* (initial state), *dominator* (reference) and *dominatee* (follower). At the beginning, all nodes are in the idle state. We assume that the sink node becomes the first dominator, then each node in the idle state applies the following rules:

- If it receives a `hello` message from a dominator, it becomes a dominatee.
- If it receives a `hello` message from a dominatee, it starts a timer inversely proportional to its weight (combination of the degree and an id). If the timer expires and the node did not receive a `hello` message from a dominator, it becomes a dominator.

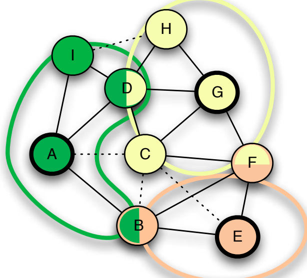
Timers used by nodes to determine their roles make the algorithm robust to frame losses. Even if a `hello` message is lost, other nodes can quickly determine their roles.

When a node changes its state, it saves the id of the originator, which is the node from which it received the corresponding `hello` message. In this way, we maintain a tree rooted at the sink. It can be easily verified that nodes alternate their roles (dominator, dominatee) along the tree. Thus, we construct a valid WCDS: any node in the network can be joined through a path of alternating dominator and dominatee nodes.

The sink increments the sequence number in each of its `hellos`. A node includes the largest sequence number received from its originator (i.e. the node that triggers its state change) in its own `hellos`. Thus, the tree *propagates hop by hop* the new sequence number. If its value remains unchanged for a long time, this means that the tree is broken somewhere at an upper level of the tree. In this case, the node reinitializes



(a) full-WCDS



(b) bridged-WCDS

Fig. 2. Examples of a full-WCDS and a bridged-WCDS.

its state, i.e. it becomes idle. The node will choose a new state only if the sequence number of a `hello` message is strictly superior to the last received sequence number—in this way, we avoid loops in the tree. When a node detects that its originator is not anymore its neighbor (e.g. no `hello` received), it proceeds in the same way.

Since the required information is piggybacked in `hellos`, the overhead only comes from an increased packet length. Besides, the time complexity of this algorithm is $O(n)$, n being the number of nodes.

D. Variants of the WCDS Structure

As each WCDS cluster uses its own virtual channel, bridge nodes need to maintain connectivity between clusters. We introduce two variants of the previous algorithm: a *full-WCDS* and a *bridged-WCDS*. We indistinctly use the terms dominator/reference and follower/dominatee in the description below.

1) full-WCDS: In this variant, a follower maintains relationships with all its neighboring references and extracts the identity and virtual channels used by its neighbors from periodical `hellos` and listens to all the virtual channels. In other words, a node that has k dominators listens to k different virtual channels. Figure 2(a) presents an example of a full-WCDS. As node C communicates with three dominators, it has to listen to all three virtual channels. It can be easily verified that all transmissions can use short preambles on synchronized links by construction.

2) bridged-WCDS: In this variant, to reduce the cost of listening to multiple virtual channels while maintaining connectivity, only a subset of common followers to two reference nodes acts as a bridge. Initially, each follower only listens to its neighboring reference node with the lowest id. Then, each reference node elects bridge nodes in a distributed way: it must elect one bridge for joining all the reference nodes with a lower id that are two hops apart. Thus, each node maintains a list of its 2-neighbors: each node includes the list of its neighbors and their states in its `hellos`. Then, a reference applies the MPR (Multi Point Relay) rule [13] to elect bridges: at each step, it chooses the follower that covers the maximum number of reference nodes until it covers all of them. Figure 2(b) shows an example of a bridged-WCDS. Since the structure is still a WCDS, all the transmissions can benefit from short preambles.

We can notice that when nodes detect a failure, they locally reconstruct the WCDS as explained previously. Thus, the reference nodes have just to maintain their neighborhood table up-to-date and keep at least one bridge node for each reference node that is two hops apart, which leads to global connectivity.

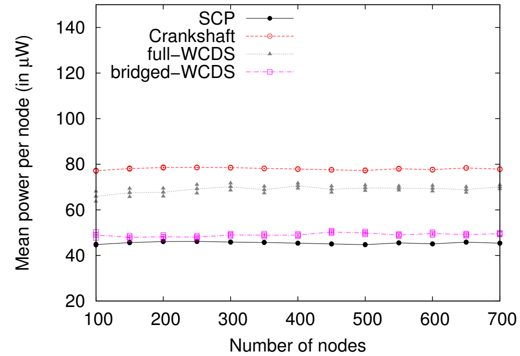


Fig. 3. Average power drained per node for synchronization and sampling in function of the network size.

V. Performance Evaluation

In this section, we evaluate the performance of the original SCP, Crankshaft, and the two variants of WCDS (full-WCDS and bridged-WCDS) proposed in this paper. We consider energy consumption and network capacity—as we aim at enabling multiple virtual channels while limiting energy consumption, we rather focus on such high-level performance criteria.

We simulate randomly generated networks with nodes that have 10 neighbors on the average (node degree). We use a unit disk communication model and plot 95% confidence intervals for all graphs.

A. Energy Consumption

For the sake of conciseness, we neglect the energy drained in processing and sensing, and only consider the energy drained in communication. We use the default values of Wavenis nodes [5]: bandwidth=19.6kbps, θ=$20 \cdot 10^{-6}$, T_{CI}=1s, T_{SI}=20min, T_{SYNC}=0.012s, T_{preamble}=0.096s, P_{tx}=45mWatt, P_{rx}=17mWatt, and $\mathcal{P}_{\mathrm{samp}}$=32.51$\mu$Watt.

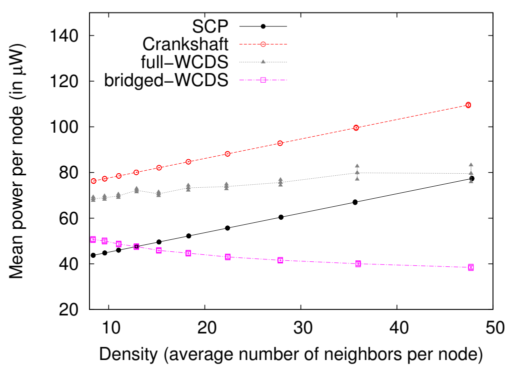


Fig. 4. Average power drained per node for synchronization and sampling in function of network density (node degree).

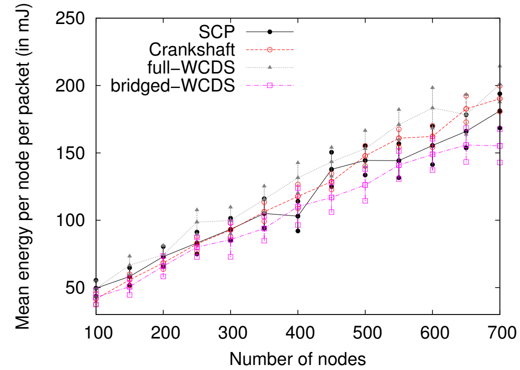


Fig. 5. Total energy per node drained in forwarding one packet in function of the network size.

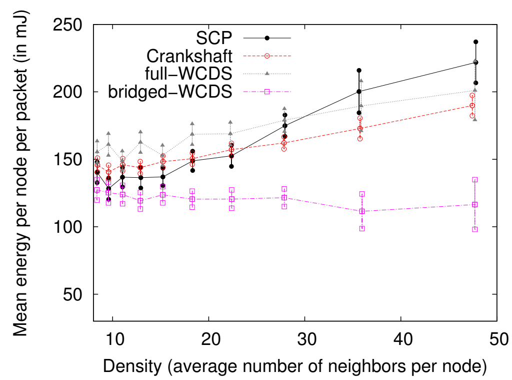


Fig. 6. Total energy per node drained in forwarding one packet in function of network density (node degree).

1) Synchronization Maintenance and Sampling: In the first experiment, we evaluate the cost of the protocols in an idle network, i.e. when there is no traffic to forward. We record the mean power consumed in channel sampling and synchronization maintenance in a network of an increasing size (cf. Figure 3). As expected, SCP consumes the lowest power, because it uses a single virtual channel for the entire network. Bridged-WCDS achieves comparable power consumption to SCP while enabling multiple virtual channels in the network. It achieves this good trade-off by reducing the cost of synchronization maintenance. Full-WCDS consumes more energy than bridged-WCDS, because follower nodes maintain more channels, but it further sustains connectivity. Crankshaft is the most consuming scheme, because each node maintains two channels. We can also see that all Synchronous Preamble Sampling schemes are scalable to large networks, because the mean power consumption remains constant when the network size increases.

We can see in Figure 4 that the mean power consumption of SCP and Crankshaft increases when the network becomes more dense. Actually, nodes have more neighbors and thus more references to listen to, which increases the synchronization cost. In contrast to that, the mean power consumption of full-WCDS remains constant. It even very slightly decreases for bridged-WCDS, because reference nodes are more uniformly distributed for higher density and slightly less bridges are required for interconnecting them.

2) Traffic Forwarding: In this experiment, we evaluate the overall energy consumption under convergecast traffic. We generate 10,000 packets (1 every 2 seconds) coming from different random sources to the sink. We measure the mean energy drained per node to transmit one packet. This includes overhearing, channel sampling, synchronization maintenance as well as traffic forwarding.

Figure 5 shows that the energy consumption per node slightly increases with the network size. This is mainly due to border effects, because in a small network, nodes at the network border have less neighbors, thus the energy drained in overhearing is reduced.

Bridged-WCDS achieves the lowest energy consumption due to the minimization of synchronization maintenance cost and the reduction of overhearing through the use of multiple virtual channels. Note that energy savings can be even better if we use overhearing avoidance methods such as those proposed earlier [14]. As bridged-WCDS reduces the energy drained in synchronization and sampling, the energy savings compared to Crankshaft will be larger if the network has less packets to forward. Full-WCDS is not so efficient since it does not aim at minimizing the number of virtual channels per follower.

Although Crankshaft further reduces overhearing by using more virtual channels, it consumes more energy because of the costs of the additional broadcast channel and synchronization maintenance.

In Figure 6, we show the impact of network density on the mean energy consumption. The results confirm that bridged-WCDS and full-WCDS can efficiently save energy compared to the other schemes.

B. Network Capacity

In a network with multiple virtual channels capacity increases, because nodes can forward more data with less contention. To evaluate network capacity, we consider that all nodes send one unit of data toward the sink and define the capacity as the inverse of the largest number of interfering transmissions on the most loaded virtual channel. We find the

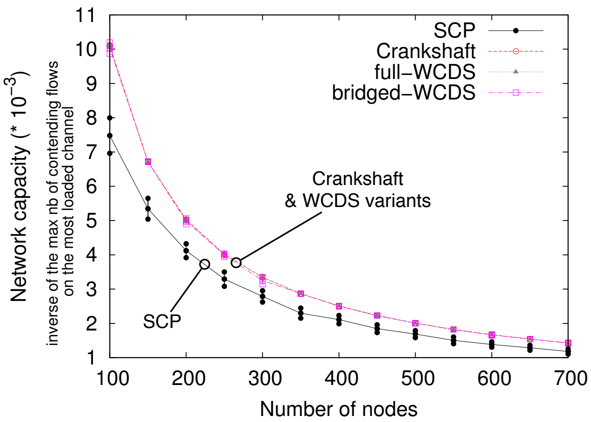


Fig. 7. Network capacity.

bottleneck set of radio links in the conflict graph[1] of a given network. First, we associate a weight corresponding to the number of forwarded packets over each radio link. We assume that each node sends one packet to the sink. Then, for each virtual channel:

1) we construct the conflict graph for a given virtual channel, i.e. the conflict graph restricted to the links that use this channel.
2) we extract the maximum weighted clique in the conflict graph. An achievable scheduling in the max-clique is a necessary condition to obtain an achievable max-min bandwidth allocation[2] [15]. Since finding this clique is NP-hard, we approximate it with a greedy polynomial approach: we sort links by a decreasing weight and add a link to the clique if it interferes with all the links already in the clique.
3) we compute the total number of transmissions in this clique equal to the sum of weights of the links.

Finally, we evaluate network capacity as the inverse of the number of transmissions over the most loaded clique (over all virtual channels).

Figure 7 presents network capacity in function of the network size. We can see that Crankshaft, full-WCDS, and bridged-WCDS offer higher network capacity compared to SCP for any number of nodes, which confirms the benefit of using multiple virtual channels. However, note that the difference decreases for large networks, because in this case contention appears around the sink even if nodes use multiple virtual channels.

VI. Conclusion and Future Work

We have proposed a new energy efficient network structure for maintaining synchronization in access methods based on Synchronous Preamble Sampling. Energy savings come from reducing the overhead of synchronization messages. Our scheme takes advantage of constructing independent clusters based on a Weakly Connected Dominating Set so that clusters can use different virtual channels and only need to maintain internal synchronization, while still offering global connectivity.

We have proposed two variants of the algorithm for distributed construction of clusters and compared their performance with major access methods for wireless sensor networks. Our simulation results show that the proposed scheme has comparable energy consumption to Scheduled Channel Polling, but results in better network capacity. Moreover, it achieves better energy savings and network capacity than Crankshaft.

In the future, we plan to consider the structure of the network that optimizes energy consumption for a dynamically varying traffic load instead of static structures.

Acknowledgments

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[1] The conflict graph associates a vertex with each radio link. Two vertices are connected iif corresponding radio links interfere with each other. Although the conflict graph represents a binary interference model (transmissions either interfere or not), it provides a good approximation of realistic radio behavior.

[2] A max-min objective in multiflow networks means that we maximize the minimum bandwidth assigned to each flow. In other words, we guarantee a minimal bandwidth per flow.

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