Utilizing the Capture Effect in low power Wireless Sensor Networks

Marvin Herrmann
University Duisburg Essen
Essen, Germany
marvin.herrmann@stud.uni-due.de

Abstract

This paper investigates the common interference called capture effect, which is subject to ongoing research interest and therefore has been analyzed in recent years by researchers in context of wireless sensor networks (WSN). The interference was studied from different perspectives and in specific network scenarios. Furthermore it is shown that the interference is directly related to the media access control (MAC) primitives and generally known effects occurring in wireless networks. Another major purpose of this work is to present insights on the capture effect by differentiating between related appliances and conclusions, and comparing these approaches to each other. This includes approaches that intentionally utilize this interference to gain desired transmission behaviour and/or optimize properties relevant to common wireless sensor networks. One of the latest attempts to benefit from the interference instead of categorically considering it as an inconvenient side effect is examined, in regard to its unusual basic approach to the effect. Previously used methods are compared with this comprehensive one, while considering network properties and environment, as well as constraints related to low power WSNs. The resulting opportunity of benefiting from the interference in an intentional manner is taken into consideration to emphasize a possible role of the capture effect in future research in the field of low power WSN MAC layer transmission primitives.

I. Introduction

A wireless sensor network (WSN) consists of a collection of devices exchanging information (data) over wireless connections. The individual devices are called motes or nodes. The physical data measured in a real world environment is gathered by sensors attached to the devices hardware interfaces (e.g. IO pins) [6]. In a typical WSN setup each source node (sender) tries to deliver this data quickly to a sink node (receiver) to ensure fast data flow utilization by software systems relying on the sensor network (e.g. big data analysis system) [14]. If no sink is in range, the data packets are forwarded over reachable adjacent nodes; ideally ensuring the fastest route with the least amount of hops to a sink is used (1:n - one-to-many relation of a source node). This configuration is called multi-hop wireless network [13]. Furthermore most WSNs are subject to resource constraints (device hardware limitations: MCU, RAM, storage, communication and sensing capabilities [6] [12]), implying saving energy is important to accomplish a long lifetime of the wirelessly interconnected sensor modules. Minimal power consumption as a basic concept leads to what is known as an ultra-low power WSN [6], where modules mostly remain in the MCU sleeping state (saving energy) and only wake up based on certain events (consuming energy). After forwarding data packets or collecting and transmitting sensor data the module enters the sleep state again (duty cycling principle [6]). A wireless network with a maximized amount of node sleep cycles is defined as a low-duty cycle network (LDC) [5] in related research, whereas a network with a minimized amount is called high-duty cycle network (HDC) [5]. This classification is based on an overall distinction between performance, energy and timing constraint driven wireless network implementations and not immensely constrained ones.

A low power WSN as an embedded part of a software system is usually in place to perform a dedicated function [5], for instance representing a sub system of a larger smart city system which acts on data measured by the WSN to facilitate controlled traffic flow in a city. Another example could be an intruder detection system (warning system), in which data collection processes are adaptive in regard to unusual measurements. Data (warnings) has to be send to an analysis instance rapidly. Depending on the chosen dedicated function a variety of promising advancements to real world applications could be implemented, underlining the role of a performance in a low energy oriented WSN usage for industrial process automation [8] and the ability to control those [8] in order to keep costs low (e.g. hardware and maintenance costs) and lifetime of the involved nodes long. In that context this paper includes insights on media access control (MAC) layer primitives, which have a significant impact on performance and energy consumption of a WSN as well, and primarily focuses on the related interference known as the capture effect, which has the potential to be beneficial to both [2] [5] [8].

The second section addresses important basic concepts and the capture effect. So called transmission primitives are explained, containing a description of MAC layer primitives defined in IEEE 802.15.4 standard [3] and low power sensor module communication relevant to understand the subsequent chapters. Different MAC layer related networking problems such as starvation [12], hidden nodes [13] and near/far effect [5] [7], that may occur in a network scenario are covered and considered in association with the capture effect. The capture effect will be defined and explained in detail, along with its possible impacts on general network properties like density, throughput and latency, which depend on the WSN resource constraints already mentioned.

The third section includes network scenarios and insights on different possibilities to utilize the capture effect for varying purposes, for instance data dissemination (flooding). Moreover these examples are compared to each other, also in association with the previous sections to view the influences of the capture effect from different angles and in specific network scenarios.

In the fourth section a more detailed and finely tuned example of utilizing the capture effect is shown. Afterwards a comparison with the prior examples will be made.

II. The Capture Effect

A. Prerequisites: Transmission Primitives

Protocols and mechanism that network communication is based on are called transmission primitives, which are part of IEEE standards. In a low-duty cycle network different sensor modules (media) try to quickly access radio frequency channels, thereby competing for the use of a specific channel (medium). This behaviour is controlled by the media access control (MAC) layer primitive [3], whose purpose is to control how a channel is shared and often to rather fictively establish fair usage of shared channels among multiple competing media. Nodes transmit frames (packets) over these channels to communicate with other nodes in the network environment. Often the concept of carrier sense multiple access with collision avoidance (CSMA/CA) is used to completely avoid collisions that may occur, when multiple mediums concurrently try to access the same channel [3]. Physical layer mechanisms like Clear channel assessment (CCA) are part of this concept, which detect noise on available channels and choose the least noisy (energy detect, CCA-ED) and decode preambles by sensing on a channel (carrier sense, CCA-CS) [3]. The CSMA/CA algorithm is the reason for a small MAC delay, which could add up over time, when transmitting frames over multiple hops [5].

A common standard for wireless personal area networks (WPAN) and utilization in WSNs is IEEE 802.15.4, which was developed to address the WSN resource constraint usage previously described. It defines the two bottom layers of the OSI-Model: physical (PHY) and media access control (MAC) layers [3]. The standard reduces the network protocol stack by one layer, hence the logical link layer is not part of it. CSMA/CA conflicts with approaches trying to benefit from exploiting interference, since it is generally assumed to avoid those per definition. This has a side effect, because frames are not intended to be transmitted with an overlapping characteristic.

The standard supports two different modes. In beacon-enabled mode (slotted mode) [3] a personal area network coordinator (PAN-Coordinator, parent node) arranges transmission intervals by using superframes. A superframe consists of a beacon at the beginning and the end, which surround a contention access period (CAP) and a contention free period (CFP) further assigned to 16 time slots [3]. Beacons are send in predefined time intervals, so that each transmitter can synchronize with the beginning of a superframe in order to compete for the usage of the medium in the CAP, specifically the available time slots, via CSMA/CA. If a transmitters attempt was successful, he gains access to his assigned time slots (the medium) and can transmit his data during the CFP period without further competition. This concept has the advantage, that each child node and the coordinator itself can save a lot of energy by cycling (sleep state) due to beacon based activity phases. In nonbeacon-enabled mode (unslotted mode), each node competes for the use of a medium (channel) only via CSMA/CA, therefore the receiving node has to stay active to continuously sense for an incoming transmission.

As defined in the IEEE 802.15.4 standard (Figure 1) [3], the first 4 bytes of a PHY layer frame represent a preamble and the fifth byte a start of frame delimiter (SFD). The synchronization word (preamble + delimiter) that has been received and decoded implies a payload (modularized signal) with a specific length (byte 6) will be decoded on the receiver's side. Usually the receiver tries to completely receive the frame after reading the synchronization word and length byte, even though signal quality/strength of the ongoing transmission can vary over time (e.g. drop or increase significantly) [14]. The last two bytes represent the checksum, which is a cyclic redundancy check (CRC) value that is used to conclude if a frame was received without alteration or symbol error [3]. The described frame format is nested into superframes, if slotted mode is used.

When a node has received a packet successfully, an acknowledgement packet (ACK) will be immediately sent to the source node. If this packet is not received, the source node (ACK-transmitter) tries to deliver the packet again repeatedly to its desired destination node (ACK-receiver) until a specified backoff period is exceeded, due to the derived conclusion of appearing transmission errors [3]. After exceeding the period a no-acknowledgement (NOACK) will be triggered [3] and an upper layer can make use of it (e.g. network layer). Generally two types of transmission errors can occur, firstly bad packet reception (symbol error [14]) and secondly transmission channel interference [7]. Bad packet reception means symbol errors [14] occurred due to the physical environment [10] for instance caused by moving machines or humans. Channel interference [7] means that two signals collided while a transmission took place. The source transmitter can't tell which error occurred, if no ACK packet was received. Also the destination node cannot tell why a packet is not correctly or never arrived. This paper goes into detail on the specific transmission channel interference known as the capture effect, why it may occurs, as well as how to control and ideally benefit from it in varying network scenarios.

In contrast to CSMA/CA the concept of carrier sense multiple access with collision detection (CSMA/CD) or code division multiple access (CDMA) can be used to regulate how collisions are handled and resolve occurring collisions or prevent them in the first place. These concepts are more power consuming than CSMA/CA and not part of the already mentioned IEEE standards for low power WSN oriented usage. Moreover those concepts are counterproductive to the investigated capture effect, hence they are not discussed in this paper.

The individual node's device radios are an important aspect of low power WSNs, due to their influence on power consumption. Most of the energy of a device is consumed by its radio [6] and their reoccurring transmitting/receiving activities. To save energy the IEEE 802.15.4 standard uses the 2,45Ghz frequency band. Even though the radios were improved over the years, they are very likely to make use of the duty-cycling principle [6] to save as much energy as possible. In the context of radio energy this is called radio duty-cycling [6], where the radio is active on interval basis (consuming energy) in order to sense on a specific channel for synchronization words. If such a word is sensed the radio stays active until the transmission is decoded and symbols are saved to a listen buffer (LX) [6], then the device enters an inactive state (saving energy) afterwards. If a packet should be transmitted to another node, it goes active and saves data to the transmit buffer (TX) [6] and with some sub steps codes encodes the data into modularized signals [14] transmitted over the mentioned frequency band.

4	1	1	Length - 2	2
Preamble	SFD	Length	Payload	Checksum

Figure 1: IEEE 802.15.4 PHY layer packet format and the relating lengths in bytes of each segment. A decoded synchronization word (preamble + SFD) implies the other segments will be recorded and decoded (transmission) [3].

B. Functional Principle & Properties

The device radios described prior transmit their message frames with different signal strengths, which depend on the device locations [11] [13], power capability constraints [6] [11], network environment [11], overall network density [13] and transmission channel configuration (carrier frequency [10]). In case of several concurrently transmitted frames [5] and under the assumption the same channels are used, the receiver's radio MAC layer primitive has to decide how to handle the transmission interference and act accordingly. Either all colliding frames are discarded (packet corruption [7]) or the stronger signal frame (high-power frames [9]) is received continuously. Therefore handling the co-channel interference [7] in a "non-corruptive" way and successfully receiving frames despite significant additional noise [7] [10] is named Capture Effect. In other words, one of the overlapping transmission somewhat survives the collision due to its greater signal power and its data is not discarded. Some radios accept very thin transmission strength differences to achieve this behaviour [7], which should not be assumed in the context of diverse low power WSNs and therefore is not assumed in the following explanations and examples regarding the capture effect. The interference takes place on the physical layer [4], but firstly MAC primitives like CSMA/CA and secondly other properties of the network facilitate the occurrence.

The transmission arrival timings (inter-packet spacing [5]) are crucial to determine why and if collisions on the receiver's side occur. The effect mentioned only takes place when a later stronger signal overlaps with a less powerful transmission signal (stronger-last [5]) or in the rare case of the same radio transmission timing intervals [13]. This scenario is visualized in Figure 2. Complementary timing obviously won't result in a capture effect (stronger-first [7]). The effect also does not occur if two synchronization words of two distinct transmissions overlap, because the receiver only processes those words as one huge synchronization word and both packets will be discarded. Additionally the occurrence of collisions while transmitting is also network environment dependent, which will be explained more detailed in the following.

The capture effect is subject to ongoing research interest, firstly due to its influence on network behaviour, performance and energy efficiency, secondly to help achieving specific, nearly deterministic, transmission behaviour [4]. This intentional behaviour will be investigated in Section III. Different methods were applied (numerical mathematics [10], e.g. markov chain model [11] [12]) to quantify the influence on parameters relevant to WSN performance (e.g. throughput and latency [2] [8] [9] [11]) and to develop models leading to improvements for varying network scenarios, as well as the MAC layer transmission primitives themselves [2] [5] [8] [9] [11] [12] [14].

The network environment in general has a huge impact on all aspects related to the capture effect. This can be easily explained with an example. A WSN is placed inside a facility in which a lot of persons and machines are moving (mobile) so that they influence the radio waves. Furthermore, the presence of tables and cabinets (stationary) influence the frequency band being used, so that it is not stable or equal on each channel at any time, due to outer physical influences (noise). This unpredictable behaviour is called fading [11] and is the reason for usage of mechanism like CCA-ED. If this phenomenon persists over longer time periods and for example is caused by a big machine or a moving node [1] it is called shadowing [11], due to its characteristic which leads to path loss [11], when a node completely looses a connection to another node. This triplet increases the likeliness, that the capture effect occurs, since the stronger-last [7] scenario can take place more often.

Several studies have shown that in networks using CSMA throughput significantly increases [9] [11] when the effect is utilized, since fewer frames are discarded. More packets can be sent instead of transmitting the same frames again to a destination node. Similarly the success rate of receiving frames is higher (packet success probability - PSP [10]). This fact indicates the duty cycling principle [6] in some studies is applied in a better way, allowing the radios of the receiver and transmitter nodes to sleep more often and save energy. No additional MAC delays caused by CSMA/CA emerge over time, so that channel sensing and retransmitting frames does not consequently reduce the throughput. Moreover studies concluded latency of involved nodes is improved, the reason being the described conjunctures which rely on MAC layer algorithms like CSMA/CA [5]. Conclusively network performance and energy efficiency is optimized although no explicit MAC protocol changes were made, singly by benefiting from the capture effect, enabled by the capture capabilities of the receiver's radio.

Network density in low power WSN is a factor that is directly related to network properties like performance and energy efficiency [13]. The factor is often seen as the hop count between a source node and a destination node. More accurate to low power WSN is the perspective of amounts of nodes in an area with different radio signal strengths and ranges that overlap partly (carrier sensing ranges [12]). Not every node can reach all nodes, network density varies among the network topology (device locations and sensing ranges) [4]. In case of high density (node density [13]) both properties suffer, due to decreased network throughput caused by CSMA. A correlation between a high amount of discarded frames (no capture) and high network density is obvious, since more concurrent transmission by other radio transmitters occur [5]. In fact not considering the capture effect falsely decreases network throughput even more in network performance analysis [10] [11] [13]. When the capture effect is considered, its influence on throughput is directly related to the network density [13]. This means in a part of the network with high density the capture effect will occur more frequently and less frequently in parts with low density [2] [7]. Only in networks with an immensely high density the probability of actually capturing a packet decreases (lower PSP) [11].

Another interesting phenomenon is the hidden nodes effect [9] [13], which is related to network density, when radio ranges of nodes just partly overlap due to different power capabilities and constraints. Ensuing from this perspective a possible scenario where two nodes are in range of one specific receiver node, but not in reach of each other, creates a problem. The problem is often present in common low power WSN topologies. This circumstance is caused by the intent to generally use as few devices as possible (see Section I, WSN usage). Two nodes transmitting to the same receiver node influence each other's transmission signals, specifically the receiving node's radio. Nearly equal signal strengths or a higher strength of one node can result in the before described stronger-last [5] scenario in which, due to the capture effect, only a single node's packets are completely received most of the time (lost fairness [12]). If a high network density is needed to fulfill topology requirements of the network, more colliding transmissions due to hidden nodes are occurring [13]. In other words the capture effect occurs more often in a high density network using CSMA/CA, even more frequently if hidden nodes effects [13] occur. In conclusion performance and energy efficiency are improved due to less discarded frames, if the radios of the nodes are capable of benefiting from the capture effect.

Starvation is also a problem worth mentioning in the context of interference, simply because the capture effect can originate it. Sticking to the last example, it means that only one node will get its packets received at any time. The other node's transmissions basically starve on their way to being complete and no packets get fully received, due to the stronger-last [5] capturing by catching the attention of the receivers radio at any time (loss of fairness [12]). When CSMA/CA is used, starvation can also occur despite the fact that packets will not be captured, usually caused by high network density and hidden nodes [4]. It is probable that nodes placed closely to the receiving node obtain the attention of the receiver at any time. This is called the near/far effect [7] [11] in which often other node's signals are not recognized anymore. Also huge distances in the node placement can originate the hidden nodes problem due to the near/far effect [7].

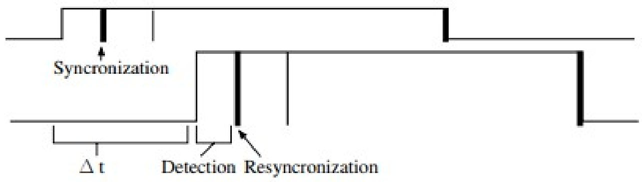

Figure 2: Stronger-last: A receiving node synchronizes with a transmission after receiving the synchronization word. Another word from a different higher powered transmission is shortly arriving (interval t) after the first one, therefore the receiver synchronizes with the latest transmission (capture effect) [5].

III. Applying the Capture Effect to different scenarios

A. Recovery

The research [7] focuses on the problem that a source transmitter cannot know why a packet was not received by a destination node if no ACK packet was processed in CSMA based networks. On the other side, the destination receiver does also not know why a packet was not correctly or never received. A procedure is proposed that can solve these problems regarding transmission errors by frequently sensing the channel for arriving synchronization words [7], even in the presence of an ongoing transmission. If that is the case, the capture effect is just appears (stronger-last [7]) and the second packet is processed. Later the first packet is retrieved, due to the already saved transmission information (synchronization word in LX buffer). That procedure opens the possibility to find out if the capture effect took place or if faulty packets due to the network environment were received. It is shown, that the procedure can be beneficial to a variety of MAC primitives, including CSMA and TDMA protocols [7]. In half of the cases the approach is successful. It is mentioned that by altering the PHY packet format with information about the packet origin, all cases could probably be measured successfully. Nevertheless this additional information is not attached, but through the approach more information is gained without changing any layer related algorithms (e.g. protocols) [7].

B. Quality of Service

In wireless sensor networks a high amount of nodes can transmit their packets over equal frequencies and channels, so that they overlap. This circumstance can lead to the necessity of prioritizing packets, so that packets are intentionally received in a specific order and based on necessarily short delivery time (low latency). Due to different WSN use case scenarios and hardware constraints the capture effect could be seen as a pervasive influence to fulfill such a requirement, rather than creating priority value labeled packets with side effects like slow delivery time and larger message overhead that does not benefit otherwise. The MAC protocol TDMA assigns each node a specific time and order related slot in which each node can send their packets [14]. If a node has nothing to transmit, a time interval is wasted, which results in an unnecessary MAC delay for other nodes. Prioritizing transmissions in this manner is called Quality of Service (QoS) differentiation [9]. These methods are used for instance in crucial health monitoring systems to obtain warning or error messages as fast as possible. Receiving and delivery times, and the order of packets are key requirements in such critical systems, therefore latency and throughput of the network has to be sufficient.

Quality of service was subject to investigation in an earlier research [9] that determined the minimal radio signal strength required to distinguish between different levels (ideal differentiation [9]) in CSMA/CA based networks, thereby creating the possibility of using the capture effect to achieve prioritized transmissions. Furthermore, the probability of receiving packets under the premise of using dissimilar powered transmissions is taken into account by calculating a success probability of capturing a packet [9]. Results show that the probability correlates with the amount of nodes (boundary) in each distinct power class (QoS priority classes). This means the amount has to be properly balanced to maintain diversity among classes, thus upper limits [9] of the node amount are proposed. The implementation of a QoS scheme via the capture effect exploit has minimal impact on the overall energy consumption of nodes, conclusively confirming the intended network behaviour has no drastic unwanted side effects on low power WSNs [9]. Equal to other research, specific network scenarios in which the results are gained have weaknesses. A low power radio signal class is prone to hidden node effects [9], described in the previous chapter. The directly related influence of network density (e.g. high density areas) was not investigated explicitly. Nevertheless, quality of connections between the nodes (e.g. changing signal strengths and physical loss) were considered via random valued factors.

Partly similar to the first example, a method using a QoS scheme in combination with different protocols was proposed [4]. The idea is to basically use a power class differentiation [9] nearly equal to the one described above in order to utilize different MAC layer algorithms like CSMA or TDMA [4], which are used by different standards for the MAC layer (see Section II). It is shown that diverse power classes are substantial to achieve the possible utilization of running different MAC layer primitives using the same medium. A WSN with a stronger-last [5] capture scenario is considered in which transmitting nodes have a thin clock difference [4] in order to schedule the transmissions accurately. The packets send to the receiving node have to overlap for the purpose of facilitating the capture effect in regard to the QoS scheme. Considering the capability of retransmitting packets, primitives assigned to lower priority classes should be able to do so, to prevent starvation. On the one hand, only low priority traffic should be consequently subject to this phenomenon [4]. On the other hand, preventing starvation is important if more than one MAC primitive with the same priority is desired. Switching between two priority classes right next to each other is suggested [4], otherwise the capture effect cannot reliably takes place. This is explainable with the stronger-last scenario, just happening two times (see Section II). As a result this research ([4]) is applicable for WSNs with varying network density, whereby the possible amount of power classes depends on density to guarantee their distinctiveness. This is a more extensive approach in comparison to the first QoS example, since different advantages of MAC primitives can be utilized via the QoS scheme and density was investigated as well. Despite of the benefits, an important difference to the other example is that the MAC primitives lose their characteristic to make use of the physical layer [4] due to the creation of different power levels. This includes time slotting [4] and transmission power control [4] on which some primitives explicitly rely on (e.g TDMA or Section C, glossy protocol). Network latency is not harmed in regard to the different power classes and their implemented primitives.

The next subsection addresses network flooding [5]. Similar to QoS a collection of nodes should receive packets, though flooding means that this collection consists of all nodes in a WSN. Therefore the described QoS examples and protocols like TDMA are not sufficient enough to guarantee high performance and low energy usage in such scenarios [5].

C. Flooding

An advanced approach to fast delivery of messages (high priority traffic) in CSMA based networks are flash flooding protocols, which were researched in several studies (e.g. [2] [5]). In [5] the capture effect is also exploited in a beneficial manner. A frame is transmitted from each node to all reachable adjacent nodes (network flooding [5]), whereby reaching all WSN nodes as fast as possible is intended (rapid flooding [2] [5]). This is implementable by using the capture effect, since normally the sender node has to wait until the transmissions of adjacent nodes are finished (significant delay). In contrast the use of the effect enables overlapping transmissions and nearly instant transmitting of nodes, so that network performance (e.g. latency, throughput) is improved drastically (near theoretical lower bound [5]) for specific frames (e.g. Section II, warning example). As examined in [5] the usage of capture effect again plays a key role in achieving such performance improvements, because concurrent signals are prioritized by exploiting capturing. It is important to point out that other network flood approaches generate better network latency and throughput via optimized transmission schemes, and hence use controlled duty-cycling phases to prevent a high amount of overlapping transmissions. This significantly reduces generally desired portability of node implementations [5], which means the application cycles used for collecting physical information are influenced. Three different flash protocols are proposed. The first is called Flash-I [5] in which a MAC protocol is disabled to remove delay caused by CSMA and CCA. All nodes send immediately to all adjacent nodes without testing if the channel is free so that many collisions are likely. This protocol with its maximized amount of concurrent transmissions does not successfully reach all nodes of the network [5], due to the capture effect (starvation problem). The second protocol, called Flash-II [5], sends frames like the first approach, but instead of avoiding MAC delay, CCA is enabled again for an additional second transmission to reach any node in the network. As a channels are not influenced (captured) during ongoing first transmissions. All nodes are reached but performance is not improved in comparison to the first approach, because of the MAC and CCA delay(s) inserted again [5]. The third protocol (Flash-III [5]) makes use of deliberately controlled CCA usage to partly prevent capturing, combined with overlapping transmissions. That means calculating the amount of overlapping transmissions present and using a CCA delay to determine when a new transmission can be initiated. To achieve less overlapping transmissions, packet transmission timings are spread out over time via delays (inter-packet spacing [5]). Considering CCA, the approach ensures reaching all nodes, otherwise MAC delays influence network performance slightly. As a result, controlled usage of the capture effect in flooding scenarios creates the opportunity to use overlapping transmissions as a useful tool to improve overall network performance in both LDC and HDC WSNs. Network density conflicts with this intended improvement in direct correlation [5], due to more overlapping transmissions (more capturing, see previous Section). In case of using Flash-III [5] or Flash-II [5] high network density is detrimental to network performance. Flash-III [5] has no significant impact on energy consumption of involved nodes. A smaller amount of packets than in other flooding protocols is forwarded through the network, so that less energy consuming phases of nodes (active state) slightly diminishes the impact of high density. This conclusion is especially relevant to LDC WSNs and the already explained low energy oriented WSN usage.

Inspired by [5] and other related work the Glossy protocol [2] based on the IEEE 802.15.4 standard was created, which implements network flooding based on node radio mechanisms (concrete signal modulation patterns) on a mainly physical level. The major difference to Flash protocols [5] is that it does not purely depend on MAC layer primitives and delay, therefore the capture effect, with the intention to overcome the previously mentioned weaknesses regarding network density. The capture effect is not required in this approach [2]. Nevertheless, if the effect is present it is a benefiting factor for reliability [2] of floods, reaching constant success values above 98% [2]. The reason for this is related to the amount of concurrent transmissions appearing, a key factor to understanding network behaviour, which was mentioned before (see Section II.B). Glossy [2] was even more improved to be more energy and performance oriented in regard to low power WSNs using the IEEE 802.15.4 standard, called Sparkle architecture [8] and WSNShape protocol [8]. This was achieved via explicitly exploiting overlapping transmissions and radio's power capabilities, so that it is possible to improve Glossy [2] in industrial facility contexts for controlling purposes [8]. An important part of the optimizations was done via the before described capture effect properties as well as the QoS attempts, furthermore the Flash III protocol [5] characteristic that measures the amount of overlapping transmissions and acts on that basis [8]. This signifies a process of understanding and utilizing the capture effect, its relation to network behaviour and properties, which is further investigated in the next section.

IV. Packet-in-packet Primitive

A. An uncommon Concept

An unusual approach to benefit from the capture effect in a stronger-last [5] scenario combined with packet injection was proposed by M. König and R. Wattenhofer in [14]. Their work is based on the IEEE 802.15.4 standard and focuses on two different network scenarios. Both are commonly seen in today's low power WSN and can potentially be improved by a finely adjusted usage of the capture effect. In this section their research will be explained in detail along with its benefits. A subsequent comparison between the before described beneficial examples to utilize the capture effect for varying purposes (e.g. network behaviour and properties) and the uncommon concept will follow in the Section V.

In the first scenario, device locations [13], network density [13][14] and outer influences caused by the network environment create a fissure (chasm [14]) within a network topology, as visualized in Figure 3. This fissure splits the WSN into two areas and is denoted by bad quality of connections between the nodes in these areas. Their idea is to overcome such a fissure in order to receive frames without the occurrence of corruption (see Section II.B) and therefore without symbol errors [14]. Interestingly enough, the researchers rebuild correct frames via a collection of frames containing symbol errors [14]. In the second scenario, a QoS scheme with a pair of low and high priority classes is investigated, neither a fissure nor divided areas exist, as visualized in Figure 4. The network properties previously mentioned are optimized with the benefit of a performance optimized QoS implementation. This is achieved through utilization of the capture effect (overlapping transmissions), by injecting a complete packet into another packets payload [14].

In the first scenario, an additional transmitting node (wakeup sender [14]) is installed, which is able to make use of the near/far effect [7] or just the capture effect. This node is placed on the not reachable side of the fissure in order to send synchronization word, length byte and a payload (maximal length [14]) with values of no interest to all usually not reachable nodes, which are characterized by having bad connections over the fissure. The initial transmitting node (cross-chasm sender [14]) which has only bad connections to the nodes on this side of the fissure, starts transmitting packets to these marginalized nodes after initially sending one synchronization packet. This synchronization packet is used for transmission scheduling (clock synchronization [14]), so that the additional node is able to send its own packets shortly before the error prone transmissions of the initial sender to interrupt ongoing transmissions. The receiving nodes process the synchronization word from the additional sender due to the capture effect and therefore try to completely receive the symbol error [14] prone packets from the cross-chasm sender [14], even though it is improbable to obtain packets that would not be discarded anyway (see Figure 5). To overcome this problem the automatic symbol decoding done by the receiver's radio is disabled in order to have control over decoding the symbols of the packet [14]. Since all receiving nodes are now collecting the error prone packets and not discard them quickly due to automatic decoding and CRC processing (checksum validation process), it is possible to try to rebuild a correct frame via the distinctly collected faulty ones.

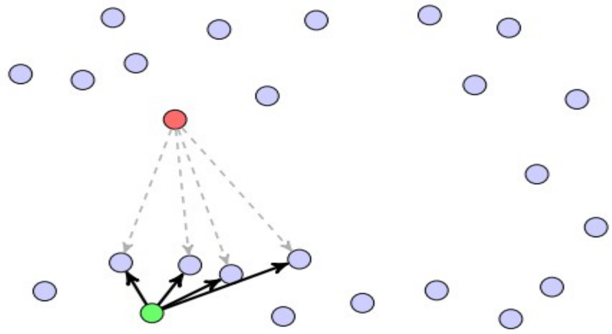

Figure 3: Scenario 1 - Fissure: The red node attemps to deliver packets over bad connections (gray) to a collection of marginalized nodes. Possibly, only an immensely long, not performance efficient and save path to those exists, therefore an additional sender (green) is installed that initializes the nodes to listen on the bad connections, so that it is possible to combine the packets [14].

Figure 4: Scenario 2 – QoS: The additional nodes try to deliver high prioritized packets (thick arrows) to receiving nodes by injecting it via capture effect into the other sender's (thin arrows) low prioritized packets [14].

Similar to the previous, the second scenario utilizes the additional node to send a maximum sized packet [14] to a receiving node, shortly before another packet arrives. This time though the additional node has a lower priority than the other sending node, which means that the stronger-last [14] scenario, possible through utilization of the capture effect, is used. This is done in order to overwrite the payload of the less prioritized transmission, specifically to encapsulate a complete high priority packet into a lower prioritized transmission packet without the creation of corruption (packet discarding due to collision). After receiving the low prioritized packet with the encapsulated packet, it is now possible that the receiving node extract and decode the high priority packet, even though if viewed from the outside a less prioritized transmission took place. In this use case it is generally anticipated that the lower power transmission packets are considerably longer than the higher ones [14], because otherwise faults in the decoding process would arise, which depends on successfully received CRC values (see Figure 6).

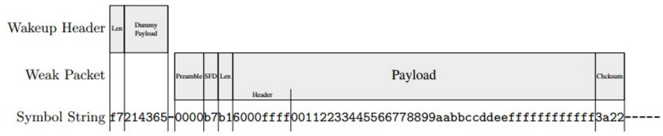

Figure 5: Symbol string - Fissure: Collection of symbols and packet segments (wakeup header + error prone packet) a node distinctly receives in the Fissure scenario. The synchronization word is already processed [14].

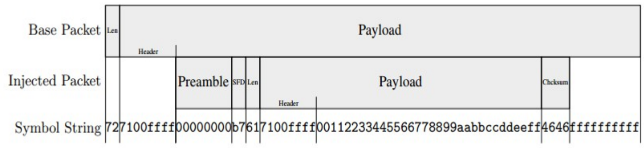

Figure 6: Symbol string - QoS: Collection of symbols and packet segments (long low priority packet with smaller injected high priority packet) a node receives in the QoS scenario. Synchronization word and CRC value of the low priority packet are already processed [14].

B. *Reconciling Transmissions*

In both scenarios, several approaches of other research are used to time the transmissions of packets that the sender node, as well as the additional sender node, transmit.

The clocks of the two sending nodes have to be well synchronized in order to ensure that their transmissions overlap in the previously described manner. To achieve this both available clocks inside the used devices are combined to obtain more precise clock timestamp values (64-bit integer) [14]. These more precise values are transmitted via the one initial synchronization packet mentioned in the scenario explanations. Likewise another approach is used to make the synchronization more accurate. A little collection of values is saved to calculate and predict the individual drifting of the devices MCU clocks (linear regression [14]). Drifting means that clocks never retain the same time, even though they were started exactly the same moment, therefore they slightly drift apart from each other over time.

Conclusively, after the first initial synchronization packet is received by the additional node, both nodes have synchronized clocks and are prepared for the next step. It is then necessary to precisely time the actual sending process.

For low power driven devices, instead of using huge time values to calculate the moment to send a packet (inaccurate calculation due to MCU resource constraints), the exact instruction cycles needed to achieve overlapping transmissions are measured. The measured amount of instruction cycles and the synchronization methods reconcile two distinct node's transmissions, so that they overlap as it is intended. For more details about these underlying approaches it is advisable to take a look at the interesting referred paper, since more detailed information about these would go beyond the limited scope of this paper.

In the second scenario, error prone packets are inserted (injected) into the payload of the first packet (see figure 4). Despite of well-timed packet injections and an upfront synchronization packet for the relatively accurately calculated injection timing, symbol errors [14] inside those injected segments occur. This can be confirmed by processing the CRC value, thus fixing these errors is a last step to gain higher symbol reception success rates (via deterministic symbol mapping [14]).

In the scenarios, it was observed that that symbol errors occur in a specific reoccurring deterministic [14] pattern. A counter procedure is introduced, which fixes these few occurring errors in both scenarios by reconstructing false symbols. A bijective formula is used to decode those false ones [14]. The bijective property of the formula, as well as the synchronization words, enable the possible of mapping specific error prone symbol strings and successfully decode them to gain less faulty symbols [14].

C. *Benefits & Weaknesses*

The results regarding the first scenario show, that an additional sender improves the possibility of receiving correct rebuilt packets by 25%. Overall a ratio of 30% is gained, taking into account the 5% of packets normally received [14]. This is the case, if the different error prone packets from the distinct receivers could be combined well enough to rebuild correct one's and symbol mapping [14] was applied. If not applied the success ratio is reduced by 5%. The probability of receiving wrong symbols at the distinct receivers was reduced by half [14], caused by using the described and underlying approaches above. This underlines the utilization of the overall method could be beneficial if it is necessary to overcome bad quality of connections between a sender node and marginalized nodes, specifically a collection of nodes separated from the rest of the network (see Section IV.A). However this is the only case in which this approach should be used, because it is not completely optimized [14]. That means more than one initial sending node could raise the probabilities in all three measured cases (see Figure 7), so that a quite low success ratios can be meaningfully improved [14]. Additionally the success rates in this scenario were harmed by the additional node partly sending wrong synchronization words [14] due to a placement behind the fissure. Altering this circumstance would potentially lead to other results. The major disadvantage of this approach is that the one synchronization packet, which has to be received by the additional node in order to let the implementation behave as intended, is improbable to be received. This is caused by the general assumption that a fissure exists, whereas somehow one specific highly important packet gets through the fissure and initializes the receiving of error prone packets (basically initializing the whole concepts process). Nevertheless in the context of bad quality of connections that occur on a non-frequent basis, it could be sufficient to at least get some rebuilt correct packets. In fact, about 70% overall failure ratio of receiving correct packets is too low to utilize the implementation on wider basis as a core concept or further developed MAC primitive [14].

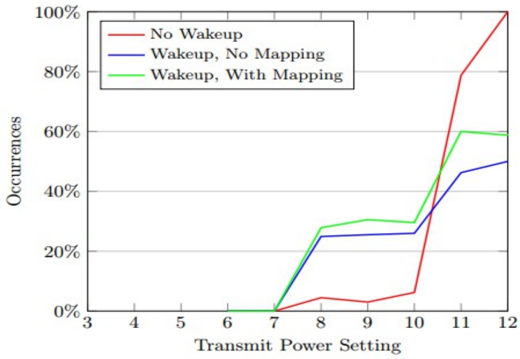

Figure 7: Results of the Fissure scenario. The additional node and the underlying approaches significantly increases the chance of rebuilding corrects packets. Also the relation to power is visualized, due its correlation to create the capture effect [14].

Regarding the second scenario, packets with a high priority (injected) could not be extracted with a possibility of about 36% [14]. For this reason the approach is partly suitable to achieve prioritized transmissions with a relatively accurate possibility (over 60%). Very low latency is the major advantage of this implementation, since high prioritized packets are immediately injected into lower prioritized ones [14]. Normally other prioritized transmissions that are ongoing create a delay, as it would be the case in the described flash protocol example. No additional labeling of packets is needed, which is only suitable if only two priority classes are used. This is quite limiting, since it reduces the possible range of scenarios in which the approach can be utilized. Such utilization could be similar to the flash flooding protocols, as well as the QoS examples explained before. In conclusion, this research is viable to be implemented in either classes of examples. That means a flooding characteristic (reach all nodes) or a QoS characteristic (reach a specific amount of nodes) can be implemented with a limited amount of priority classes. Nevertheless the concept relies on the length of the lower prioritized packets to function properly and as intended (injecting), which again implicates limits; thus less scenarios that would benefit.

V. Conclusions & Prospect

As this work demonstrated a low energy oriented usage of low power WSNs depends on the MAC layer primitives used, especially the usage of the CSMA protocol which is defined in the IEEE 802.15.4 and 802.11 standards. It is very interesting to see that the capture effect properties only very slightly vary if any of these standards is used, due to the CSMA protocol which has a major impact and can be/is used in both. Therefore the 802.11 standard was not explicitly mentioned. One difference between these standards are mechanisms like beacon mode or handshaking (RTS/CTS) to control the usage of a channel and decide when a collection of nodes can send data over it. Since the 802.15.4 standard directly addresses low power WSNs and non-beacon mode can also be used, the research based on the other standard is mentioned only in regard to show which possibilities the capture effect offers. All influenced network properties related to the effect depend on wireless connectivity and are explained in the context of CSMA. The results in this section highly overlap, thus only very thin differences in the usage of the two standards can normally be neglected in the context of low power WSNs. Furthermore in most of the examples it is pointed out, that CSMA along with the capture effect is the key factor to achieve specific results. The newer examples all use the 802.15.4 standard. Partly MAC protocols are adapted or disabled to create the possibility to benefit from the effect. This means since the capture effect is largely independent from these two standards, it is advised to use the newer 802.15.4 standard in the context of low power WSNs.

In the past the capture effect was utilized to regulate specific network behaviour with a reasonable ability to control it and improve performance in low power WSNs. More and more the capture effect is being better understood and employed for more precise functionality. No longer will only overlapped transmissions be exploited, but more finely adjusted usage is being investigated. The concept of packet injection in connection with the capture effect is a first proof of concept whose possibilities are not yet fully discovered. Currently this concept solves problems, which will occur more frequently in the future, due to the increasing amount of low power WSNs being placed into our every day life as well as the working environment. Nevertheless the solution has side effects which should be subject to further research to compensate them to a certain amount. The concept of manipulating packets has great potential to be utilized for other purposes. This could for example be creating new packets out of a few collected ones. Also the context of security is very interesting and might warrant further study, since packets are manipulated but are still accepted. In critical low power WSN infrastructures this aspect could become increasingly important. The capture effect is already quite relevant and further innovations are to be expected in the near future.

References

[1] F. Ferraro. M. Zimmerling, L. Mottola, and L. Thiele. Low-power wireless bus. In The 10 th ACM conference on Embedded Nework Sensor Systems, SenSys '12, Toronto, ON, Canada, November 6-9, 2012, pages1-14. ACM, 2012.

[2] F. Ferrari, M. Zimmerling, L. Thiele, and o. Saukh. Efficient nework flooding and time synchronization with glossy. In proceedings of the 10 th International Conference on Information Processing in Sensor Networks, IPSN 2011, April 12-14, 2011, Chicago, IL, USA, pages 73-84. IEEE, 2011.

[3] Institute of Electrial and Electronics Engineers. IEEE Standard 802.15.4: Wireless Medium Access Control (MAC) and Physical Layer (PHY) Specifications for Low-Rate Wireless Personal Area Networks (LR-WPANs).

[4] M. König and R. Wattenhofer. Sharing a medium between concurrent protocols without overhead using the capture effect. In proceedings of the International Conference on Embedded Wireless Systems and Networks, EWSN 2016, Graz, Austria, 15-17 February 2016, pages 113-124. Junction Publishing, Canada / ACM, 2016.

[5] J. Lu and K. Whitehouse. Flash flooding: Exploiting the capture effect for rapid flooding in wireless sensor networks. In INFOCOM 2009. 28 th IEEE International Conference on Computer Communications, 19-25 April 2009, Rio de Janeiro, Brazil pages 2491-2499. IEEE, 2009.

[6] J. Polastre, R. Szewczyk, and D. E. Culler. Telos: enabling ultra-low power wireless research. In Proceedings of the Fourth International Symposium on Information Processing in Sensor Networks, IPSN 2005, April 25-27, 2005, UCLA, Los Angeles, California, USA, pages 364-369. IEEE, 2005.

[7] K. Whitehouse, A. Woo, F. Jiang, J. Polastre, and D. Culler. Exploiting the capture effect for collision detection and recovery. In Proceedings of the 2 nd IEEE Workshop on Embedded Networked Sensors, pages 45-52. IEEE Computer Society, 2005.

[8] D. Yuan, M. Riecker, and M. Hollick. Making 'glossy' networks sparkle: Exploiting concurrent transmissions for energy efficient, reliable, ultra-low latency communication in wireless control networks. In Wireless Sensor Networks – 11 th European Conference, EWSN 2014, Oxford, UK, February 17-19, 2014, Proceedings, volume 8354 of Lecture Notes in Computer Science, pages 133-149. Springer, 2014.

[9] Alfandika Nyandoro, Lavy Libman, and Mahbub Hassan. Service Diffentiation Using the Capture Effect in 802.11 Wireless LANs. In IEEE Transactions on Wireless Communications, Volume 6, Issue 8, August 2007.

[10] Cengiz Gezer, Chiara Buratti, and Roberto Verdone. Capture effect in IEEE 802.15.4 networks: Modelling and experimentation. In Wireless Pervasive Computing (ISWPC), 5 th IEEE International Symposium, 5-7 May, Modena, Italy, 2010.

[11] Xiaolong Li, and Qing-An Zeng. Capture Effect in the IEEE 802.11 WLANs with Rayleigh Fading, Shadowing, and Path Loss. In Wireless and Mobile Computing, Networking and Communications, 2006. (WiMob'2006). IEEE International Conference 19-21 June, Montreal, Que., Canada, 2006.

[12] M. Durvy, O. Dousse, and P. Thiran. Modeling the 802.11 Protocol Under Different Capture and Sensing Capabilities. In INFOCOM 2007, 26 th IEEE International Conference on Computer Communications, 6-12 Maym. Barcelona, Spain 2007.

[13] H. Zhao, E. Garcia-Palacios, S. Wang, J. Wei, and D. Ma. Evaluating the impact of network density, hidden nodes and capture effect throughput guarantee in multi-hop wireless networks. In Elsevier B.V. Ad Hoc Networks 2012, SciVerse ScienceDirect. University of Defense Technology, China and University of Belfast, United Kingdom.

[14] M. König, and R. Wattenhofer. Effectively Capturing Attention Using the Capture Effect. In SenSys 2016, 14-16 Stanford. CA, USA 2016.