ENHANCED COLLISION AVOIDANCE MECHANISMS FOR WIRELESS SENSOR NETWORKS THROUGH HIGH ACCURACY COLLISION MODELING

BEHNAM DEZFOULI

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Universiti Teknologi Malaysia

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To my wife, Marjan,
to my parents, Hamid and Giti,
to my brothers, Amir, Majid and Mehrdad,
to my sister-in-law, Tahereh

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ABSTRACT

Wireless channel and multi-hop communications cause a significant number of packet collisions in Wireless Sensor Networks (WSNs). Although a collision may cause packet loss and reduce network performance, low-power wireless transceivers allow packet reception in the presence of collisions if at least one signal can provide a sufficiently high power compared with other signals. Therefore, with respect to the large number of nodes used in WSNs, which necessitates the use of simulation for protocol development, collisions should be addressed at two layers: First, collisions should be modeled at the physical layer through a high-accuracy packet reception algorithm that decides about packet reception in the presence of collisions. Second, collision avoidance mechanisms should be employed at the Medium Access Control (MAC) layer to reduce packet losses caused by collisions. Unfortunately, the existing packet reception algorithms exhibit low accuracy and impede the development of efficient collision avoidance mechanisms. From the collision avoidance perspective, existing contention-based MAC protocols do not provide reliable packet broadcasting, thereby affecting the initialization performance of WSNs. In addition, despite the benefits of schedule-based MAC protocols during the data-gathering phase, the existing mechanisms rely on unrealistic assumptions. The first major contribution of this work is CApture Modeling Algorithm (CAMA), which enables collision modeling with high accuracy and efficiency at the physical layer. The higher accuracy of CAMA against existing approaches is validated through extensive comparisons with empirical experiments. The second major contribution includes mechanisms that improve the reliability of packet broadcasting. In particular, adaptive contention window adjustment mechanisms and the Geowindow algorithm are proposed for collision avoidance during the initialization phases. These mechanisms considerably improve the accuracy of the initialization phases, without violating duration and energy efficiency requirements. As the third major contribution, a distributed and concurrent link-scheduling algorithm (called DICSA) is proposed for collision avoidance during the data-gathering phase. DICSA provides faster slot assignment, higher spatial reuse and lower energy consumption, compared with existing algorithms. Furthermore, evaluating DICSA within a MAC protocol confirms its higher throughput, higher delivery ratio, and lower end-to-end delay.

ABSTRAK

Komunikasi multi-lompatan dan saluran tanpa wayar menyebabkan sejumlah pelanggaran paket yang ketara dalam Rangkaian Penderia Tanpa Wayar (WSN). Walaupun pelanggaran boleh mengakibatkan kehilangan paket dan menurunkan prestasi rangkaian, penghantar-terima tanpa wayar berkuasa rendah membenarkan penerimaan paket dengan kehadiran pelanggaran jika sekurang-kurangnya satu isyarat dapat menyediakan kuasa tinggi yang mencukupi berbanding dengan isyarat lain. Maka, bagi bilangan nod yang banyak digunakan di dalam WSN yang memerlukan penggunaan simulasi untuk pembangunan protokol, pelanggaran harus ditangani pada dua lapisan. Pertama, pelanggaran sepatutnya dimodel pada lapisan fizikal menerusi algoritma penerimaan paket yang tepat yang menentukan penerimaan paket dalam kehadiran pelanggaran. Kedua, mekanisme pengelakan pelanggaran seharusnya digunakan pada Medium Kawalan Akses (MAC) bagi mengurangkan kehilangan paket yang disebabkan pelanggaran. Malangnya, algoritma penerimaan paket sedia ada menunjukkan ketepatan yang rendah dan menghalang pembangunan mekanisme pengelakan pelanggaran yang efisien. Dari perspektif pengelakan pelanggaran, protokol MAC berasaskan perlumbaan yang ada tidak memberikan penyiaran paket yang boleh dipercayai, seterusnya memberi kesan kepada prestasi permulaan WSN. Di samping itu, walaupun ada kebaikan pada protokol MAC berasaskan penjadualan semasa fasa pengumpulan data, mekanisme sedia ada bergantung kepada andaian yang tidak realistik. Sumbangan utama kajian ini ialah Algoritma Permodelan Penangkapan (CAMA) yang memungkinkan permodelan pelanggaran dengan ketepatan dan keberkesanan yang tinggi pada lapisan fizikal. Ketepatan CAMA yang lebih tinggi berbanding kaedah sedia ada disahkan melalui perbandingan-perbandingan yang menyeluruh dengan eksperimen empirikal. Sumbangan utama kedua adalah mekanisme yang meningkatkan kebolehpercayaan penyiaran paket. Khususnya, penyesuaian mekanisme pelarasan tetingkap pertelagahan dan algoritma *Geowindow* dicadangkan untuk pengelakan pelanggaran semasa fasa-fasa permulaan. Mekanisme tersebut dengan jelas meningkatkan ketepatan pada fasa permulaan tanpa menyalahi keperluan tempoh dan keberkesanan tenaga. Sumbangan ketiga penting ialah Algoritma Penjadualan Pautan Teragih dan Serentak (DICSA) dicadangkan bagi pengelakan pelanggaran semasa fasa pengumpulan data. DICSA menyediakan penentuan slot yang lebih cepat, penggunaan semula ruang yang lebih tinggi dan penggunaan tenaga yang lebih rendah dibandingkan dengan algoritma sedia ada. Tambahan pula, penilaian DICSA dalam protokol MAC membuktikan truput yang lebih tinggi, kadar penghantaran yang lebih tinggi dan nisbah kelewatan yang lebih rendah.

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LIST OF ABBREVIATIONS

ACK	–	Acknowledgement
BEB	–	Binary Exponential Backoff
BER	–	Bit Error Rate
BFS	–	Breadth First Search
CAMA	–	CApture Modeling Algorithm
CDMA	–	Code Division Multiple Access
CI	–	Constant Interval
CRC	–	Cyclic Redundancy Check
CSMA	–	Carrier Sense Multiple Access
CSMA/CA	–	Carrier Sense Multiple Access/Collision Avoidance
CTC	–	Collection Tree Construction
CTM	–	Capture Threshold Model
CTMA	–	CTM-based packet reception Algorithm
CTS	–	Clear To Send
CW	–	Contention Window
DCF	–	Distributed Coordination Function
DICSA	–	DIstributed and Concurrent link Scheduling Algorithm
DRAND	–	Distributed RANDomized scheduling
DSSS	–	Direct-Sequence Spread Spectrum
DOI	–	Degree Of Irregularity
ECDF	–	Empirical Cumulative Distribution Function
ETX	–	Expected number of Transmissions
FCS	–	Frame Check Sequence
FDMA	–	Frequency Division Multiple Access
Geowindow	–	Geometric-distribution-based contention window adjustment
LPL	–	Low-Power Listening
MAC	–	Medium Access Control
MPDU	–	MAC Protocol Data Unit

NCFSK	–	Non-Coherent Frequency Shit Keying
NCR	–	Neighborhood-aware Contention Resolution
NDLE	–	Neighbor Discovery and Link Estimation
NP	–	Non Polynomial
OQPSK	–	Offset Quadrature Phase-Shift Keying
PDF	–	Probability Density Function
PRR	–	Packet Reception Rate
PSM	–	Primary State Machine
RF	–	Radio Frequency
RIM	–	Radio Irregularity Model
RMSE	–	Root Mean Square Error
RS	–	Reception Slot
RSSI	–	Received Signal Strength Indicator
RSO	–	Reception Slot of One-hop neighbor
RTS	–	Request To Send
RX	–	Reception
SEEDEX	–	SEED EXchange scheduling
SFD	–	Start of Frame Delimiter
SNR	–	Signal-to-Noise Ratio
SINR	–	Signal-to-Interference-plus-Noise Ratio
SINRA	–	SINR-based packet reception Algorithm
SSM	–	Secondary State Machine
TDMA	–	Time Division Multiple Access
TX	–	Transmission
UDG	–	Unit Disk Graph
VDEC	–	Vizing-based Distributed Edge Coloring
VDOI	–	Variance of Degree Of Irregularity
WSN	–	Wireless Sensor Network

LIST OF SYMBOLS

$\mathbf{A}$ – Anisotropy matrix
$B(x, y)$ – Binomial random variable with x trials and success probability y
B_n – Noise bandwidth
$c_{i,j}$ – Link cost between node i and node j
$C_{tx,rx}$ – Correlation between transmission power and noise floor heterogeneity
$cost_i$ – Cost of node i towards the sink
CS_{th} – Carrier-sensing threshold
$\mathbf{CN}_i$ – Set of the contenders of node i
CW_c – Congestion contention window size
CW_N – N-th sub-contention window
CW_i – Initial contention window size
CW^{δ} – Contention window duration in terms of the number of backoff slots
CW^{δ}_{th} – Minimum acceptable number of backoff slots in a sub-contention window
d – Distance
d_0 – Reference distance
d_{cs} – Carrier-sensing distance
$d_{i,j}$ – Distance between node i and node j
d_{prop} – Propagation range
E_b – Energy per bit
E^{δ}_N – End of N-th contention window
f_c – Carrier frequency
F_n – Noise figure
h – Number of hops to destination
k – Boltzmann constant
K_{θ} – Path-loss coefficient at direction θ

$l_{i,j}$ – The link between node i and node j

L_{packet} – Number of bits in a packet

$L_{settling}$ – Number of settling bits

maxC – Maximum number of children per node

maxN^1 – Maximum neighborhood size

maxN^{1,2} – Maximum one-hop and two-hop neighborhood size

$N(x, y)$ – Gaussian random variable with mean x and standard deviation y

N_0 – Spectral noise density

N_{node} – Number of nodes in the network

$\overline{\mathrm{N}^1}$ – The average number of one-hop neighbors per node

$\overline{\mathrm{N}^2}$ – The average number of two-hop neighbors per node

$\mathbf{N}_i^1$ – The set of the one-hop neighbors of node i

$\mathbf{N}_i^2$ – The set of two-hop neighbors of node i

$\mathbf{N}_i^{pending}$ – The set of neighbors from which node i expects to receive response during a time slot reservation round

p – Forward link quality

$PL(d)$ – Path loss at distance d

$PL(d_0)$ – Path loss at reference distance d_0

$\Pr(\overline{\mathrm{bit}})$ – Bit error probability

$\Pr(\mathrm{packet})$ – Packet reception probability

q – Backward link quality

R – Transceiver bit rate

$\mathbf{RS}(i)$ – Set of the reception time slots of node i

$\mathbf{RSO}(i)$ – Set of the reception time slots of one-hop neighbors of node i

$\mathbf{S}$ – The set of the signals currently being received at a node

S_i – A signal corresponding to a packet sent by a node

S_N^δ – Start of N-th contention window

$S_i(t_m, t_n)$ – A signal that starts at time t_m and finishes at time t_n

$S_i^{CR}(t_m, t_n)$ – Complete reception of packet i during t_m to t_n

$S_i^{PR}(t_m, t_n)$ – Partial reception of packet i during t_m to t_n

$SINR_{th}$ – Threshold SINR value

$SINR_j(S_i)$ – SINR value corresponding to signal S_i received at node j

$SINR_j(S_i, t)$ – SINR value corresponding to signal S_i received at node j at time t

T_{packet} – Packet transmission duration

T^{δ}_{packet} – Packet transmission duration in terms of the number of backoff slots

$\mathbf{TS}(i)$ – Set of the transmission time slots of node i

$\mathbf{TSO}(i)$ – Set of the transmission time slots of one-hop neighbors of node i

$\mathbf{TST}(i)$ – Set of the transmission time slots of two-hop neighbors of node i

$W(x, y)$ – Weibull random variable with scale parameter x and shape parameter y

V_i – A sample node in the network

$\mathbf{V}$ – Set of nodes in the network

X_{area} – Width of the area

γ – Minimum link cost between a node and its neighbors

$\boldsymbol{\Gamma}_{i\rightarrow j}$ – The set of nodes that their transmission time overlap (fully or partially) with the packet reception from node i at node j

δ_i – Selected backoff slot by node i

ζ – Total propagation, encoding and decoding delays

η – Path-loss exponent

θ – Degree of a given direction

ϑ – Speed of light

κ_j^t – Priority of node j at time slot t

λ – Rate parameter of the geometric distribution

$\Lambda\left(c_{j,i}, \lambda\right)$ – The probability of cost broadcast by node j after receiving a cost packet from node i

ϖ – Maximum transceiver switching delay

ϱ – Environmental temperature

σ_{ch} – Standard deviation of signal power variations caused by multipath channel

σ_{rx} – Standard deviation of noise floor heterogeneity

σ_{tx} – Standard deviation of transmission power heterogeneity

σ_{WGN} – Standard deviation of additive white Gaussian noise

τ – Synchronization accuracy

υ – One-way message delay

$\Upsilon(x)$ – The distance at which a specific packet reception rate (x) is achieved

$\varphi_{i,j}$ – A link belonging to set $\mathbf{\Phi}_l^u$

$\mathbf{\Phi}_l^u$ – Those links between a node and its neighbors that the floor of their ETX cost is in range $[l, u]$

$\Psi_j(S_i)$ – Reception power corresponding to signal S_i received at node j

$\Psi_j(S_i, t)$ – Reception power received at node j at time t corresponding to signal S_i

$\bar{\Psi}$ – Average noise floor

$\bar{\Psi}_i^{adj}$ – Adjusted noise floor of node i considering hardware heterogeneity

$\bar{\Psi}_i^{adj}(t)$ – Adjusted noise floor of node i at time t

Ω_i – Output power corresponding to node i

Ω_i^{adj} – Adjusted output power of node i considering hardware heterogeneity

$< i, k, o >$ – A time slot reservation entry indicating i as sender, k as receiver, and o as the reserved time slot

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CHAPTER 1

INTRODUCTION

1.1 Overview

Wireless Sensor Network (WSN)s are currently being used for various applications, ranging from medical monitoring to military surveillance [1, 2]. A WSN is composed of nodes with scarce energy resources, therefore, low-power Radio Frequency (RF) transceivers and microcontrollers are employed in the design of wireless sensor nodes. Meanwhile, wireless transceiver spends most of a node's energy and makes efficient wireless communications a very challenging problem [3].

Since the wireless channel is a broadcast medium, each node's transmission propagates in all directions and affects other nodes based on the distance from the sender. In addition, due to the use of low-power wireless communications, WSNs operate in a distributed manner and employ multi-hop packet forwarding. With respect to these issues, while the packet corresponding to the signal transmitted by a node may be received at the intended receiver, this signal may act as an interfering signal for other ongoing communications. In other words, when two nodes are communicating, usually the signal being received from the sender is overlapped with other interfering signals. Therefore, as each node's transmission may cause interference on other nodes, the term *packet collision* (or simply *collision*) would better reflect interference. Generally, collision is defined as below [4, 5],

Definition 1.1. *Collision.* When at least one signal is present at a node, the arrival of each subsequent signal causes a collision.

Since interference can also be generated by the sources outside the network (*e.g.,* IEEE 802.11 and Bluetooth networks) [6, 7], the term ”collision” only refers to the interference caused by network nodes. Nevertheless, this thesis explicitly employs the term ”external interference” for those collisions caused by sources outside the network.

Since WSNs are highly collision-prone, various collision avoidance mechanisms have been proposed to overcome the negative effects of collisions. However, although collisions affect packet reception performance [3, 8, 9], they may not necessarily cause packet loss. Specifically, *the capture effect*, also called *interference tolerance* [10], is the ability of a transceiver to receive a signal in the presence of interfering signals as long as the Signal-to-Interference-plus-Noise Ratio (SINR) of the signal being received is above a certain threshold value [4, 11, 12]. The capture effect is supported by most of low-power RF transceivers (*e.g.,* CC1000 [13] and CC2420 [14]) and it has a significant effect on packet reception performance when packets are subject to collision [4, 11, 12, 15–18]. Therefore, as a collision may not cause packet corruption, the literature usually employs definitions that are more specific. For example, the literature on Medium Access Control (MAC) mechanisms normally focuses on those collisions that cause packet corruption. Similarly, in this thesis, while Definition 1.1 is particularly useful for collision analysis and modeling from the physical-layer point of view, related but different definitions are used for the analyses preformed from the MAC-layer perspective.

Most of the applications of WSNs usually employ a large number of nodes (*viz.,* hundreds or even thousands of nodes). Therefore, since empirical experiment with a large number of nodes is very costly and time consuming, researchers rely on simulation for protocol development and evaluation. Accordingly, dealing with collisions in WSNs should be considered from two highly correlated point of views, which are corresponding to the physical layer and MAC layer:

(i) **Physical Layer.** As WSNs are collision-prone, usually two or more signals arrive and overlap at the physical layer of the nodes. In other words, each signal arriving at the physical layer usually overlaps with other signals with various powers and durations. Therefore, collisions highly affect the performance of wireless networks [19–24]. The *packet reception algorithm* (*a.k.a., packet reception model*) employed at the physical layer is responsible to model collisions and make decision about the reception of incoming packets. Especially, it is mainly the responsibility of the packet reception algorithm to represent the real behavior of low-power

RF transceivers. Inaccuracy of collision modeling avoids revealing the real efficiency of collision avoidance mechanisms, highly affects the operation and performance of higher-layer protocols, and hinders cross-layer protocol optimizations through the physical layer [9, 25–27]. Accordingly, various interference models and packet reception algorithms have been proposed by the literature (*e.g.,* [19, 20, 28–33]).

(ii) **MAC Layer.** As a collision may cause a packet loss, it affects the reliability and energy efficiency of transmissions. In addition, when a transmitted packet is not received at its intended receiver, it unnecessarily occupies the channel and results in lower effective throughput. Furthermore, as stated earlier, collisions affect the performance of higher-layer protocols. For example, packet losses during the data-gathering phase of WSNs reduce the number of packets delivered to the sink node, and this directly affects the application for which the network has been deployed. Therefore, many efforts have been made to improve network performance through collision avoidance mechanisms. Specifically, since the MAC layer manages access to the common channel, collision avoidance is mainly addressed at this layer through channel access mechanisms [3, 34–38]. However, it should be noted that a collision avoidance mechanism should not necessarily be implemented at the MAC layer. For example, a module implemented above the MAC layer can improve and manage the operation of a MAC protocol.

1.2 Problem Background

As accurate collision modeling is crucial for the design, development and evaluation of collision avoidance mechanisms, this section, first, studies the challenges of collision modeling. Then, it proceeds with the challenges of providing collision avoidance during the operational phases of WSNs.

1.2.1 Collision Modeling

As stated earlier, collision modeling requires employing a packet reception algorithm at the physical layer to evaluate the incoming signals and model the effects of collisions on packet reception. Meanwhile, a packet reception algorithm relies on an interference model [20, 29, 33] (*e.g.,* SINR, Capture Threshold Model (CTM)) to decide whether an incoming packet should be received and how collisions affect an ongoing reception [19, 28, 30, 31, 39].

There are, in general, two approaches for designing a packet reception algorithm: (i) *packet-level modeling* is computationally efficient but do not accurately reproduce many aspects of collisions with respect to the capture effect; (ii) *physical-level modeling* has high fidelity but is computationally infeasible to be used for long, multi-packet network traces or large-scale networks such as WSNs. Packet-level algorithms typically perform one or two evaluation to determine the effects of collisions on a signal being received [20, 28, 31, 40, 41]. From the simulation point of view, packet-level modeling requires a lightweight algorithm and provides fast simulation. Unfortunately, packet-level algorithms present drawbacks as follows [4, 20, 27, 28, 30, 31, 39]:

(i) *Inaccuracy of Collision Modeling and Packet Reception.* When multiple signals collide at a receiver, these algorithms cannot correctly decide which packet should be received. In comparison with a real-world scenario, either these algorithms indicate correct reception for the packets that could not be actually received, or they do not receive the packets that could be actually received. The inaccuracy of these algorithms is mainly due to the incorrect representation of the real behavior of low-power RF transceivers in terms of the capture effect and transceiver synchronization [4, 20, 28, 30, 31]. For example, when a strong signal collides with the beginning of a weaker signal, although it might be possible to receive the weaker signal correctly, these algorithms do not represent any reception. In particular, as the accuracy of these models depends on the factors such as collision intensity, signal arrival times, MAC protocol operation and packet format, they do not provide an accurate solution for collision modeling.

(ii) *Lack of Collision Recovery, Partial Packet Reception, and Collision Detection.* Since most of the commonly used RF transceivers support the capture effect, they can switch to a new packet reception after a collision that corrupts the packet currently being received. Therefore, subject to the power of a newly arrived signal, transceivers may recover from a collision. Furthermore, depending on the collision time, some data parts of the corrupted packet may have been correctly received. These received bytes can be delivered by the physical layer to the higher layers [4, 27]. Collision recovery and partial packet reception also allow the MAC layer to perform collision detection. These features are particularly useful for the optimization of higher layers (*e.g.,* [9, 18, 25–27]). However, packet-level algorithms do not provide partial packet reception because these features depend on accurate modeling of the capture effect, transceiver synchronization modeling, and the SINR values computed during specific fields or bits of the packet. Consequently, packet-level algorithms cannot be used to develop or analyze cross-layer protocol optimization.

On the other hand, physical-level modeling requires SINR calculations at the bit-level; therefore, providing the upper-layer protocols with a high-fidelity estimate of collision impact. Unfortunately, physical-level modeling is very expensive from the computational point of view. It involves a comparison of the signal strength of every possible transmitter at all possible receivers for every bit. Therefore, the overhead of these algorithms scales with the number of bits per packet, the number of packets sent, and the square of the number of nodes in the network. This approach is particularly infeasible in large-scale WSNs with low-power MAC protocols, many of which use extremely long preambles or packet cycling techniques (*e.g.,* [35, 42, 43]). Therefore, new techniques are needed to achieve collision modeling with high accuracy and low overhead.

While collision modeling enables the nodes to make decision about the reception of the incoming signals, the power of the signals received at each node depends on the collision relationship between nodes. Recent studies on low-power wireless communications revealed particular characteristics (*e.g.,* radio irregularity and hardware heterogeneity) that highly affect collision relationship between nodes [44–49]. In other words, in addition to the well-known models of signal propagation (*e.g.,* log-normal shadowing model), these models also affect the signal power level each node receives from other nodes. For example, assume that these models are neglected, and the transmission of node i causes a collision of power x on node j. After considering the radio irregularity and hardware heterogeneity models, the received signal power from node i at node j changes to x', and this change might affect packet reception performance at node j. On the other hand, the accuracy and performance of collision avoidance mechanisms depend on collision relationship between nodes [44, 50–52]. For example, contention-based collision avoidance mechanisms highly rely on the carrier sensing information received from the physical layer. In addition, schedule-based collision avoidance mechanisms rely on collision relationship between nodes for channel access scheduling. Therefore, accurate collision modeling would be meaningless without establishing precise collision relationship between nodes [29]. Although the literature proposes models for establishing precise collision relationship between nodes, unfortunately, investigating the implementation architectures used for implementing these models on simulation platforms indicates the lack of these models. Consequently, for example, the real-world performance of a link-scheduling algorithm (used for collision avoidance during the data-gathering phase) may be highly different than the result obtained by simulation [50, 52]. Therefore, implementing an accurate packet reception algorithm along with the models that affect collision relationship between nodes requires a sophisticated architecture. Using this architecture, the aforementioned algorithms and models can be implemented on a simulation platform such as OMNeT++ [53].

1.2.2 Collision Avoidance

As stated earlier, WSNs are highly collision-prone, therefore, collision avoidance mechanisms are required to improve the performance of these networks. This thesis addresses collision avoidance with respect to the actual operational phases of WSNs: initialization, and data gathering. Therefore, collision avoidance should be investigated according to the particular characteristics of each phase. For each phase, before presenting the importance and challenges of collision avoidance, the operation of that phase is described.

1.2.2.1 Collision Avoidance during the Initialization Phases

The initialization phase has two sub-phases: Neighbor Discovery and Link Estimation (NDLE), and Collection Tree Construction (CTC). Since WSNs operate in a distributed manner, a NDLE protocol should be executed after network deployment to gather neighborhood information and estimate link qualities [54–60]. This information is later used by protocols such as routing and MAC to perform their operation [61, 62]. In addition, since the main observable traffic pattern in WSNs is many-to-one (*a.k.a., convergecast*) [3, 63–65], it is the responsibility of the CTC phase to establish efficient paths from each node towards the sink [64, 66–69]. Consequently, NDLE and CTC are the essential phases to operationalize a WSN.

During the NDLE phase, nodes should broadcast a fixed number of beacon packets to identify their neighbors and estimate their link qualities [54, 56, 58, 59, 62, 70]. Similarly, CTC is a packet flooding (started from the sink node) in which every node broadcasts its minimum cost towards the sink [64, 67–69]. Consequently, collisions highly affect the accuracy of these phases because they rely on a significant number of broadcast transmissions. During the NDLE phase, for those missing beacon packets caused by collision, nodes cannot distinguish between the packet losses caused by link unreliability and those caused by collisions. Therefore, a node that misses a beacon packet cannot properly estimate its link cost to the node from which the packet has been originated. In addition, collisions affect the number of discovered neighbors. Packet collision during the CTC phase causes cost update failure and increases the cost of the constructed tree, compared with the optimal-cost tree. Particularly, missing a cost packet not only affects the node that has lost the packet, but it also affects the path cost of the nodes that could have used this node as their ancestor. The inaccuracies introduced by the NDLE and CTC phases affect the efficiency of higher-layer protocols. For example, the inaccuracy of neighbor discovery affects the efficiency of scheduling algorithms, because they rely on neighborhood information to assign collision-free time slots to the nodes. In addition, inaccurate estimation of the links prevents the routing protocol to perform efficient packet forwarding. Furthermore, the inaccuracy of the CTC phase results in data transmission over non-optimal paths and causes lower delivery ratio, longer delay and higher energy consumption.

Contention-based channel access (*a.k.a.,* Carrier Sense Multiple Access (CSMA)) is the only possible way to arbitrate channel access during the NDLE and CTC phases, because: First, as these phases are executed after network deployment, nodes do not have any neighborhood information, therefore, sophisticated channel access mechanisms (*e.g.,* [38, 71]) cannot be employed. Second, the initialization phases should provide adaptive and fast initialization using lightweight protocols with minimum overhead. On the other hand, achieving reliable broadcasting through CSMA is a challenging problem due to the following reasons: First, no contention window adjustment can be applied because collision detection through mutual handshaking or Acknowledgement (ACK) is not possible with broadcast transmissions [72–76]. Second, utilizing multiple unicast transmissions instead of a broadcast transmission is not feasible because it requires the nodes to be aware of their neighbors, which is not available at the network initialization [77]. In addition, unicast transmissions significantly increase the duration and energy consumption of the initial phases [56]. Unfortunately, although the literature proposes many MAC protocols for improving the reliability of unicast transmissions during the data-gathering phase, no considerable contribution can be found on improving broadcast reliability during the initialization phases [3, 5, 56, 64, 78].

The most straightforward way to improve broadcast reliability is to broadcast multiple copies of each packet. Although this approach has been used in vehicular networks (*e.g.,* [79, 80]), it cannot be used during the NDLE phase of WSNs, because this phase requires a predetermined number of transmissions. In addition, as this approach multiplies the duration and energy consumption, it is not useful for the CTC phase. Considering the challenges of achieving broadcast reliability, conservative approaches such as extra-large backoff duration and constant beaconing interval have been used to reduce collisions [56, 62, 64]. However, these approaches do not provide collision detection and they are not adaptive to network dynamics. Specifically, due to the influence of various parameters (such as network density, transmission power, path loss, beacon length and transceiver speed) on the number of collisions, it is hard to achieve a trade-off between accuracy and duration. This is even more challenging when no exact network density can be considered for large-scale WSNs with random deployment. For example, the fixed beaconing rate approach either has been used in small-scale networks [61], or it has a very long inter-packet interval. These discussions indicate that CSMA should be improved through adaptive and efficient collision avoidance mechanisms for the broadcast traffic pattern.

1.2.2.2 Collision Avoidance during the Data-Gathering Phase

The fundamental traffic pattern observable in WSNs is packet forwarding towards the sink node [36, 63, 81–83]. A WSN enters this phase after the initialization phases. In order to make accurate and quick decisions, data-gathering applications usually require high delivery ratio with minimum end-to-end delay [81–84]. From the channel access perspective, employing contention-based access mechanisms during this phase results in a significant number of collisions, which is the result of traffic direction, multi-hop packet forwarding, and more importantly hidden-node collisions. Since collisions reduce network performance in terms of effective throughput and delivery ratio, scheduling algorithms have been proposed to eliminate the negative effects of collisions on the performance of data-gathering applications [3, 36, 85]. Accordingly, the literature proposes two types of scheduling algorithms: *Node-scheduling algorithms* assume each node's transmission should be received by all of its neighbors. Therefore, they assign time slots to the nodes to avoid those collisions that may cause a node's transmission to be corrupted at any of its neighbors. In contrast, *link-scheduling algorithms* assume a specific direction for each transmission. In this instance, the collision avoidance strategy is to avoid those collisions that may cause packet corruption at the intended receiver of each packet.

Since link-scheduling algorithms rely on transmission directions, time slot assignment is less constrained and fewer number of time slots can be used for transmission scheduling. Therefore, link-scheduling algorithms provide higher spatial reuse, which results in elevated network throughput [37, 86, 87]. Besides, as the CTC phase establishes an almost static child-parent relationship between nodes, it justifies the benefits of employing link scheduling for improving the performance of data-gathering phase [36, 88, 89]. However, while most of these algorithms are centralized (*e.g.,* [90–93]), others rely on specific assumptions that are not realistic in WSNs (*e.g.,* the requirement to have an interference-free tree topology [94, 95]). In particular, despite significant research on the theoretical aspects of collision avoidance through link scheduling, less attention has been paid to the design of practical scheduling algorithms. Meanwhile, DRAND [38, 61] is a distributed node-scheduling algorithm that does not require any assumption regarding the underlying network. However, considering the convergecast traffic pattern, this algorithm cannot achieve the potential improvements of link scheduling. For example, even if the transmissions of two neighboring nodes to their parents do not cause packet corruption, DRAND prevents concurrent transmission of these nodes. Beside this drawback, as DRAND does not allow one-hop and two-hop neighbors to concurrently apply for time slot reservation, nodes should perform their time slot assignment sequentially. The lack of concurrency increases the execution duration and energy consumption of this algorithm. Based on these discussions, a fast, distributed and applicable link-scheduling algorithm is required to improve packet transmission efficiency during the data-gathering phase.

1.3 Problem Statement

Considering the negative effects of collisions, each node should employ collision avoidance mechanisms to avoid packet corruption at the intended receivers. Although collisions increase the chance of packet corruption at a receiver, the capture effect provides certain conditions under which a packet can be received in the presence of collisions; therefore, accurate collision modeling is required at the physical layer. The previous discussions have revealed the importance and challenges of collision modeling and avoidance from the physical layer (corresponding to packet reception) and MAC layer (corresponding to packet transmission) point of views, respectively. At the physical layer, a sophisticated packet reception algorithm is required to improve the accuracy of collision modeling. At the MAC layer, efficient collision avoidance mechanisms are required to improve the performance of WSNs. This section further elaborates these problems.

1.3.1 First Research Problem: Collision Modeling with High Accuracy and Efficiency

As WSNs are highly collision-prone, a packet reception algorithm is required at the physical layer of the nodes to evaluate the incoming signals and decide about the delivery of the incoming packets to the MAC layer. Unfortunately, *the existing packet reception algorithms do not represent accurate collision modeling in terms of decision making about packet reception in the presence of collisions.* Specifically, these algorithms do not accurately model the capture effect, and do not provide partial packet reception and collision detection. On the other hand, physical-level packet reception modeling has not been used because of its high complexity and overhead. To overcome these problems the following research question should be addressed:

RESEARCH QUESTION 1.1. How to design and develop a physical-level packet reception algorithm with the following properties: (i) it provides high accuracy in modeling the influence of collisions with respect to the capture effect and signal synchronization; (ii) it is an efficient solution (*i.e.,* number of nodes and packet size do not compromise its accuracy and speed); (iii) it supports partial packet reception and collision detection; (iv) it is independent of the implementation of the higher-layer protocols.

The implementation, evaluation and use of the above-mentioned packet reception algorithm on a simulation platform requires an implementation architecture. Furthermore, accurate collision modeling at the physical layer would be meaningless without establishing precise collision relationship between nodes. Unfortunately, *the existing implementation architectures do not support the implementation and evaluation of the above-mentioned packet reception algorithm, and these architectures do not include most of the essential models that affect collision relationship between nodes.* Therefore, the following question arises:

RESEARCH QUESTION 1.2. How to design and develop an implementation architecture through which the aforementioned packet reception algorithm and the existing models that affect collision relationship between nodes can be implemented on a simulation platform?

1.3.2 Second Research Problem: Adaptive and Efficient Collision Avoidance during the Initialization Phases

Contention-based channel access is the only mechanism that can be employed for channel arbitration during the initialization phases of WSNs. However, *as contention-based channel access mechanisms do not provide collision avoidance for broadcast transmissions, the accuracy and efficiency of the initialization phases are highly affected by collisions.* Therefore, with respect to the considerable influence of the initialization phases on network performance, efficient collision avoidance mechanisms are required. Since the traffic pattern of NDLE and CTC phases are slightly different, the above problem leads to two questions:

Research Question 2.1. How to adaptively and efficiently improve broadcast reliability through contention-based channel access mechanism during the NDLE phase?

Research Question 2.2. How to adaptively and efficiently improve broadcast reliability through contention-based channel access mechanism during the CTC phase?

1.3.3 Third Research Problem: Fast and Distributed Link Scheduling for Collision Avoidance during the Data-Gathering Phase

With respect to the convergecast traffic pattern, many scheduling algorithms have been developed for collision avoidance during the data-gathering phase. However, *compared with node scheduling, although link scheduling provides higher collision avoidance efficiency for the convergecast traffic pattern, existing link-scheduling algorithms rely on specific assumptions that cannot be satisfied in real-world applications.* To overcome this problem the following research question should be addressed:

Research Question 3.1. How to design and develop a distributed, fast and applicable link-scheduling algorithm for the data-gathering phase?

1.4 Objectives

The main aim of this research is improving collision modeling through a packet reception algorithm, as well as improving network performance through collision avoidance mechanisms. To achieve these aims, the following objectives are defined:

(i) To analyze collisions and collision modeling algorithms through empirical and simulated experiments.

(ii) To design and develop a physical-level packet reception algorithm to achieve collision modeling and decision making about packet reception with high accuracy and efficiency.

(iii) To validate the high accuracy and efficiency of the packet reception algorithm proposed in (ii) through comparing the results of simulated and empirical experiments.

(iv) To design and develop channel access mechanisms for providing adaptive and efficient collision avoidance during the initialization phases.

(v) To evaluate the performance of the collision avoidance mechanisms proposed in (iv) through extensive simulation studies.

(vi) To design and develop a distributed, fast and applicable link-scheduling algorithm for efficient collision avoidance during the data-gathering phase.

(vii) To evaluate the performance of the link-scheduling algorithm proposed in (vi) through extensive simulation studies.

1.5 Contributions

In order to achieve the aforementioned objectives, the following contributions are presented by this work:

(i) This research presents the following contributions with respect to collision modeling and analysis:

    (a) A physical-level packet reception algorithm, called CApture Modeling Algorithm (CAMA), with high accuracy and efficiency. CAMA is designed based on the real characteristics of low-power RF transceivers and it also employs mechanisms for reducing the overhead of high accuracy collision modeling. In addition to accuracy, CAMA also provides partial packet reception and collision detection, which are useful for cross-layer optimization of higher layers.

    (b) An implementation architecture through which CAMA can be implemented on a simulation platform. This architecture also allows the implementation of the existing models that impact collision relationship between nodes.

    (c) Empirical analysis of collisions with low-power RF transceivers. These studies reveal how collisions affect packet reception, partial packet reception, and collision detection performance. While comparison with empirical results confirms the credibility of CAMA, these evaluations also show the higher accuracy of CAMA against existing packet reception algorithms.

    (d) Sensitivity analysis of collisions, and in particular the capture effect, against various environmental and network parameters. This study exhibits the importance of collision modeling, and shows how environmental and network parameters affect the efficiency of packet reception and collision detection.

(ii) This research presents the following contributions for achieving collision avoidance and improving the reliability of packet broadcasting during the initialization phases:

    (a) Contention window adjustment mechanisms for collision avoidance during the NDLE phase. These mechanisms benefit from the collision detection capability of CAMA, and they can provide adaptive collision avoidance with respect to local collision intensity. These mechanisms considerably improve the accuracy of NDLE without violating the energy efficiency requirement of WSNs. Furthermore, since CAMA is the underlying physical layer, the NDLE protocol is enabled to benefit from partially received packets.

    (b) A mathematical model through which the contention window size can be adjusted to achieve a desired collision avoidance probability during broadcast transmissions. This model can be used for collision analysis and pre-deployment configuration of MAC protocols.

    (c) The Geometric-distribution-based contention window adjustment (Geowindow) algorithm, which reduces collisions during the CTC phase through contention window size management and transmission prioritization. This algorithm results in significant improvement of CTC accuracy without increasing duration or energy consumption.

(iii) This research presents the following contribution for collision avoidance during the data-gathering phase:

    (a) A distributed and concurrent link-scheduling algorithm, called DICSA. DICSA does not require any assumption regarding the underlying network, and achieves fast and flexible time slot assignment. These features translate to the higher performance of data-gathering applications, as well as lower schedule recovery cost in the presence of network dynamics.

1.6 Significance of the Research

Literature review and the experiments presented in this thesis confirm that WSNs are highly collision-prone, and this issue significantly affects the performance of these networks. Therefore, both collision modeling and collision avoidance are essential for protocol development and improving the performance of WSNs. This research addresses collision modeling at the physical layer, because it is responsible for modeling the effects of collisions on packet reception. Collision avoidance is addressed at the MAC layer, because it controls channel access. With respect to the presented contributions, this section highlights the significance of this research:

(i) The comprehensive empirical measurements presented in this thesis highlight packet reception performance in the presence of collisions. Through comparison with the results of simulated experiments, these studies inform the researchers about the unacceptable accuracy of the existing collision modeling approaches on which all the higher-layer protocol developments are relied.

(ii) The comprehensive simulation-based sensitivity analyses allow the researchers to consider the effects of environmental and network parameters on collision intensity, collision detection and packet reception performance.

(iii) As WSNs are highly collision-prone, the proposed packet reception algorithm (*i.e.,* CAMA) is particularly important for protocol development and performance prediction. In addition, this algorithm presents new opportunities to the researchers to employ partial packet reception and collision detection for cross-layer improvement of higher-layer protocols.

(iv) The proposed implementation architecture can be used to implement

CAMA and the essential models of low-power wireless communications on simulation platforms. This enables the research community to regenerate the real characteristics of low-power wireless communications.

(v) Collision avoidance during the initialization phases affects the performance of network protocols such as routing and MAC. For example, improving NDLE and CTC accuracy results in higher energy efficiency, higher delivery ratio, and lower delay.

(vi) The proposed mechanisms for providing broadcast reliability during the initialization phases achieve collision avoidance based on local collision intensity. Therefore, they are very useful for applications that include a large-scale network with random topology.

(vii) Collision avoidance during the data-gathering phase directly affects network performance. For example, collision avoidance during this phase results in higher energy efficiency, higher network throughput, and lower delay.

(viii) The proposed link-scheduling algorithm provides fast, distributed and applicable collision avoidance during the data-gathering phase. As most of the WSN applications involve data reporting to a single base station, many applications can be envisaged for this algorithm.

1.7 Scope

The followings clarify the scope of this research:

(i) This work addresses the collision avoidance problem at the MAC layer, because it controls transceiver operation. However, collision avoidance can also be addressed by network-layer mechanisms (*e.g.,* packet forwarding through less congested paths), physical-layer mechanisms (*e.g.,* rate control), and so forth.

(ii) This work considers the effects of white Gaussian noise. However, the influence of external interference on collisions has not been considered.

(iii) This work assumes all the nodes employ a single channel for communications.

(iv) This work addresses collision avoidance through mechanisms that manage access to a common channel. Therefore, mechanisms such as Frequency Division Multiple Access (FDMA) or Code Division Multiple Access

(CDMA) are out of the scope of this work.

(v) The empirical validations presented in this thesis employ the two most commonly used low-power RF transceivers, *i.e.,* CC1000 and CC2420. These transceivers are used in sensor nodes such as Mica2, TelosB and MicaZ, which have been widely utilized by the research community. This thesis does not present any validation against other low-power transceivers (such as CC2500 [96] and CC2520 [97]) or the transceivers employed in IEEE 802.11 [75] and 802.15.6 [98] networks.

(vi) This work does not perform performance evaluation in mobile WSNs, nevertheless,

  (a) The packet reception algorithm and the architecture proposed in Chapter 4 support node mobility given that the received transmission power during a packet reception is unaffected by mobility.

  (b) The mechanisms proposed in Chapter 5 can also be employed for collision avoidance in mobile WSNs. However, it should be noted that, depending on the mobility level, mobile WSNs might employ methods such as opportunistic routing instead of packet forwarding through collection tree.

  (c) The scheduling algorithm proposed in Chapter 6 can support limited mobility. Specifically, it is assumed that node movement, node addition and node removal (or death) are very unlikely. However, this algorithm can be adapted to sporadic changes in network topology.

1.8 Thesis Organization

The remaining of this thesis is organized as follows. Chapter 2 provides the background of this research through studying the collision modeling and collision avoidance approaches. Chapter 3 presents the overall research plan and the performance evaluation platforms of this research. Chapter 4 proposes CAMA and an implementation architecture. In addition, this chapter presents extensive empirical and simulated experiments for analyzing collisions in WSNs. Chapter 5 deals with collision avoidance during the initialization phases of WSNs. First, this chapter proposes mechanisms for improving broadcast reliability during the NDLE phase. Then, it focuses on improving the accuracy of CTC phase through collision avoidance. Through proposing a link-scheduling algorithm, Chapter 6 overcomes the negative effects of collisions during the data-gathering phase. Chapter 7 concludes this research and provides directions for future work.

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