Abstract

Wireless sensors are a key technology for many current or envisioned applications in industry and sectors such as biomedical engineering. In this context, magnetic induction has been proposed as a suitable propagation mechanism for wireless communication, power transfer and localization in applications that demand a small node size or operation in challenging media such as body tissue, fluids or soil. Magnetic induction furthermore allows for load modulation at passive tags as well as improving a link by placing passive resonant relay coils between transmitter and receiver. The existing research literature on these topics mostly addresses static links in well-defined arrangement, i.e. coaxial or coplanar coils. Likewise, most studies on passive relaying consider coil arrangements with equidistant spacing on a line or grid. These assumptions are incompatible with the reality of many sensor applications where the position and orientation of sensor nodes is determined by their movement or deployment.

This thesis addresses these shortcomings by studying the effects and opportunities in wireless magnetic induction systems with arbitrary coil positions and orientations. As prerequisite, we introduce appropriate models for near- and far-field coupling between electrically small coils. Based thereon we present a general system model for magneto-inductive networks, applicable to both power transfer and communication with an arbitrary arrangement of transmitters, receivers and passive relays. The model accounts for strong coupling, noise correlation, matching circuits, frequency selectivity, and relevant communication-theoretic nuances.

The next major part studies magnetic induction links between nodes with random coil orientations (uniform distribution in 3D). The resulting random coil coupling gives rise to a fading-type channel; the statistics are derived analytically and the communication-theoretic implications are investigated in detail. The study concerns near- and far-field propagation modes. We show that links between single-coil nodes exhibit catastrophic reliability: the asymptotic outage probability $\epsilon \propto \mathrm{SNR}^{-1/2}$ for pure near-field or pure far-field propagation, i.e. the diversity order is 1/2 (even 1/4 for load modulation). The diversity order increases to 1 in the transition between near and far field. We furthermore study the channel statistics and implications for randomly oriented coil arrays with various spatial diversity schemes.

A subsequent study of magneto-inductive passive relaying reveals that arbitrarily deployed passive relays give rise to another fading-type channel: the channel coefficient is governed by a non-coherent sum of phasors, resulting in frequency-selective fluctuations similar to multipath radio channels. We demonstrate reliable performance gains when these fluctuations are utilized with spectrally aware signaling (e.g. waterfilling) and that optimization of the relay loads offers further and significant gains.

We proceed with an investigation of the performance limits of wireless-powered medical in-body sensors in terms of their magneto-inductive data transmission capabilities, either with a transmit amplifier or load modulation, in free space or conductive medium (muscle tissue). A large coil array is thereby assumed as power source and data sink. We employ previous insights to derive design criteria and study the interplay of high node density, passive relaying, channel knowledge and transmit cooperation in detail. A particular focus is put on the minimum sensor-side coil size that allows for reliable uplink transmission.

The developed models are then used in a study of the fundamental limits of node localization based on observations of magneto-inductive channels to fixed anchor coils. In particular, we focus on the joint estimation of position and orientation of a single-coil node and derive the Cramér-Rao lower bound on the estimation error for the case of complex Gaussian observation errors. For the five-dimensional non-convex estimation problem we propose an alternating least-squares algorithm with adaptive weighting that beats the state of the art in terms of robustness and runtime. We then present a calibrated system implementation of this paradigm, operating at 500 kHz and comprising eight flat anchor coils around a $3\,\text{m} \times 3\,\text{m}$ area. The agent is mounted on a positioner device to establish a reliable ground truth for calibration and evaluation; the system achieves a median position error of 3 cm. We investigate the practical performance limits and dominant error source, which are not covered by existing literature.

The thesis is complemented by a novel scheme for distance estimation between two wireless nodes based on knowledge of their wideband radio channels to one or multiple auxiliary observer nodes. By exploiting mathematical synergies with our theory of randomly oriented coils we utilize the random directions of multipath components for distance estimation in rich multipath propagation. In particular we derive closed-form distance estimation rules based on the differences of path delays of the extractable multipath components for various important cases. The scheme does not require precise clock synchronization, line of sight, or knowledge of the observer positions.

Kurzfassung

Drahtlose Sensoren gelten als Schlüsseltechnologie für viele aktuelle und künftige Anwendungen, etwa industrieller Art oder in der Medizintechnik. Magnetische Induktion gilt als geeigneter Ausbreitungsmechanismus für drahtlose Kommunikation, Energieübertragung und Positionsbestimmung in Sensoranwendungen, die nur sehr kleine Geräte erlauben oder in schwierigen Umgebungen operieren, z.B. in Gewebe, Flüssigkeiten oder unterirdisch. Magnetische Induktion ermöglicht darüber hinaus Lastmodulation an passiven Sensoren sowie Übertragungsverbesserungen durch das Platzieren von passiven resonanten Relayspulen zwischen Sender und Empfänger. Die dazugehörige Fachliteratur befasst sich hauptsächlich mit wohldefinierten Anordnungen von koaxialen oder koplanaren Spulen, welche äquidistant auf einer Linie oder Gitter platziert sind. Diese Annahmen sind jedoch unvereinbar mit der Realität vieler Sensoranwendungen, in denen Knotenpositionen und -ausrichtungen meist durch Mobilität oder Einsatzzweck bestimmt sind.

Diese Arbeit reagiert auf diese Mängel, indem die Auswirkungen und Möglichkeiten von beliebigen Spulenpositionen und -ausrichtungen in magnetisch-induktiven Übertragungssystemen untersucht werden. Vorbereitend führen wir adäquate Modelle für Nah- und Fernfeldkopplung zwischen elektrisch kleinen Spulen ein. Darauf aufbauend präsentieren wir ein allgemeines Systemmodell, das Energieübertragung und Kommunikation in einer beliebigen Anordnung von Sendespulen, Empfangsspulen und passiven Relays beschreibt. Das Modell berücksichtigt starke Kopplung, Rauschkorrelation, Anpassung, Frequenzabhängigkeit und relevante kommunikationstheoretische Nuancen.

Der nächste grosse Abschnitt befasst sich mit der Übertragung zwischen Spulen mit zufälliger Ausrichtung (Gleichverteilung in 3D), wobei die resultierende zufällige Spulenkopplung zu einem Fadingkanal führt. Wir leiten dessen statistische Verteilung her und untersuchen die kommunikationstheoretischen Eigenschaften sowohl für Nah- als auch Fernfeldausbreitung. Wir zeigen, dass die Übertragung zwischen einzelner solcher Spulen katastrophale Zuverlässigkeit aufweist: Die asymptotische Ausfallwahrscheinlichkeit erfüllt $\epsilon \propto \mathrm{SNR}^{-1/2}$ für reine Nah- oder Fernfeldausbreitung, d.h. der Diversitätsexponent beträgt 1/2 (sogar 1/4 für Lastmodulation). Wir zeigen, dass der Wert im Nah-Fern-Übergang auf 1 steigt. Des Weiteren studieren wir räumliche Diversitätsverfahren für zufällig gedrehte Spulenarrays und die resultierende Kanalstatistik.

Ein Abschnitt über passive Relays zeigt zunächst, dass diese in zufälliger Anordnung ebenfalls Fading hervorrufen: Eine nicht kohärenten Summe von komplexwertigen Zeigern bestimmt den Kanalkoeffizienten, was (ähnlich der Mehrwegeausbreitung) frequenzabhängige Schwankungen zur Folge hat. Wir demonstrieren, dass die Nutzung dieser Schwankungen mittels sendeseitiger Kanalkenntnis (z.B. Waterfilling) und vor allem die Optimierung der Relaylasten verlässlich für erhebliche Verbesserungen sorgen.

Ein weiterführender Teil untersucht die Performancegrenzen sehr kleiner medizinischer in-vivo Sensoren in puncto induktiver Datenübertragung, entweder mittels Sendeverstärker oder Lastmodulation, für Freiraumausbreitung oder in einem leitenden Medium (Muskelgewebe). Ein grosses Spulenarray ausserhalb des Körpers wird als Leistungsquelle und Datensenke betrachtet. Wir leiten Designkriterien aus früheren Erkenntnisse ab und untersuchen die Auswirkungen hoher Knotendichte, passivem Relaying, Kanalkenntnis und kooperativer Übertragung im Detail. Ein besonderer Fokus liegt auf der minimalen sensorseitigen Spulengrösse für zuverlässige Übertragung.

Die entwickelten Modelle werden dann in einer Untersuchung der magnetisch-induktiven Knotenlokalisierung, basierend auf Kanalmessungen zu Ankerspulen, verwendet. Der Fokus liegt auf den grundlegenden Grenzen der gemeinsamen Schätzung von Position und Ausrichtung eines Knotens; hierfür wird die Cramér-Rao-Schranke für den Fall komplexer Gaussscher Messfehler hergeleitet. Für dieses fünfdimensionale nichtkonvexe Schätzproblem schlagen wir eine alternierende und adaptiv gewichtete Methode der kleinsten Quadrate vor, die hinsichtlich Robustheit und Laufzeit den Stand der Technik schlägt. Anschliessend stellen wir eine kalibrierte Systemimplementierung dieses Paradigmas vor, die bei 500 kHz arbeitet und acht flache Ankerspulen um eine $3\,\mathrm{m} \times 3\,\mathrm{m}$ Fläche verwendet. Um eine zuverlässige Ground Truth für Kalibrierung und Auswertung sicherzustellen ist der mobile Knoten auf einer Positioniervorrichtung montiert. Das System erreicht einen Medianpositionsfehler von 3 cm. Wir untersuchen die praktischen Leistungsgrenzen und die (im momentanen Wissenstand unbekannte) dominante Fehlerquelle solcher Systeme.

Ein ergänzendes Kapitel widmet sich einem neuen Ansatz zur Abstandsschätzung zwischen zwei drahtlosen Knoten, deren breitbandige Funkkanäle zu einem oder mehreren Beobachtern bekannt sind. Dabei nutzen wir die zufälligen Richtungen von Mehrwegekomponenten bei ausgeprägter Mehrwegeausbreitung aus. Basierend auf den Verzögerungsunterschieden der extrahierbaren Mehrwegekomponenten leiten wir Abstandsschätzungsformeln für mehrere wichtige Fälle her. Der Ansatz erfordert weder genaue Synchronisation, Sichtverbindung noch Kenntnis der Beobachterpositionen.

Chapter 1

Motivation and Contributions

This chapter describes contemporary research goals regarding wireless sensors and the associated need for wireless communication, powering, and localization. We discuss the potential benefits of magnetic induction and our goals in this context, associated open research problems, the corresponding state of the art and its shortcomings as well as the structure and contributions of this dissertation.

1.1 Wireless Sensors: Technological Situation

Information and communication technology has revolutionized most processes in industry, health care, business administration and daily life. In particular, remarkable advances in integrated circuits, computing, sensors, displays and battery technology gave rise to powerful wireless communication technology. Prominent examples are tablet computers and smart phones equipped with antennas and chipsets for local area networking via the IEEE 802.11ac standard [1], cellular networking via LTE-Advanced [2], and reception of navigation satellite signals. They are capable of *reliable digital communication over wireless channels* with high data rate and can *determine their location* within a few meters of accuracy [3]. These devices are rather large and expensive [4] and have considerable energy consumption [5, 6]. Apart from such consumer electronics, modern wireless communication technology also finds important uses in devices for sensing and actuation (henceforth referred to as *wireless sensors*). The topic has received a lot of attention by the wireless industry and research community, mostly under the umbrella of *wireless sensor networks* (WSN) [7–11] and the *Internet of Things* (IoT) [12–15]. Wireless sensors are used for all kinds of sensing and monitoring tasks in the military [9, 16], power grid [17], large machines [18] and a multitude of industrial processes [10]. Envisioned environmental applications comprise the detection of hazardous materials and contamination cleanup [19]. Medical in-body applications of wireless sensors could disrupt the field of health care: future *medical microrobots* are expected to provide untethered diagnostic sensing, targeted drug delivery and treatment (e.g. removing a kidney stone or tumor) [20–25].

Wireless sensors rely on wireless technology to transmit acquired sensor data, receive commands, coordinate actions, and to determine their location [8, 26]. Their *technical requirements and limitations* are however stricter than those of consumer electronics. First, many target applications require wireless sensors to be deployed in vast numbers, which constrains the unit cost and thus also the hardware complexity. Secondly, wireless sensors are usually battery-powered but required to stay operational for a long period of time [7]. The use of low-power hardware and transmission schemes can remedy the problem [11, 27, 28], but even despite these measures a wireless sensor may be energy-limited to an extend where the fulfillment of its basic tasks is in jeopardy. This holds especially for the task of transmitting vast data to a remote data sink [28, 29]. The problem is even more pronounced when the maximum device size is constrained by the application [23, 26, 30, 31]: with current technology, a severely size-constrained wireless sensor can not be equipped with a battery of any useful capacity [26] (although some progress is made in that regard [32]). A prime example are medical microrobots which must be sufficiently small to fit in cavities of the human body in a minimally invasive way. Their application-specific maximum device size ranges from $\approx 3\,\mathrm{cm}$ for gastrointestinal cameras down to a few µm for maneuvering the finest capillary vessels [22, 23, 31]. As an alternative to a battery, energy can be supplied via the electromagnetic field (wireless power transfer) [7, 33, 34] or gathered from environmental processes (energy harvesting) [14, 35].

Most contemporary wireless technology relies on conventional radio with antennas whose size is matched to the employed wavelength λ for efficient radiation and reception of electromagnetic waves. It is the technology of choice for long-range communication because the link amplitude gain h (a.k.a. channel coefficient) of a free-space radio link decays with only $h \propto r^{-1}$ versus the link distance r. *Conventional radio is however inadequate for certain wireless sensor applications.* The link gain is usually way below $-50\,\mathrm{dB}$ and thus insufficient for wireless power transfer [36, Fig. 5.1]. Further significant attenuation occurs when an antenna shall fit into a small device because then the realizable aperture is limited [37, Sec. 8.4]. Likewise, for conventional radio, a maximum antenna size implies a maximum wavelength λ, i.e. a minimum carrier frequency f_c. For example, a dipole antenna whose $\lambda/2$ length is set to just $0.5\,\mathrm{mm}$ (e.g. because it is integrated into a medical microrobot) radiates efficiently at $f_\mathrm{c} = 300\,\mathrm{GHz}$. Fields of such large frequency may however be subject to severe medium attenuation [38], e.g. caused by conducting body fluids and tissue [39, 40]. Other challenging propagation environments for wireless sensor applications are the underground [41–43], underwater [44], oil reservoirs [45–48], engines [18], hydraulic systems [48] and battlefields [9].

High-frequency radio waves interact with the environment: they are reflected, scattered and diffracted by objects. They are thus hard to predict in dense environments [49], which constitutes a huge problem for accurate radio localization. In particular, multipath propagation and non-line-of-sight situations deteriorate time-of-arrival localization schemes [50] and, likewise, the associated multipath fading and shadowing cause fluctuations that deteriorate received-signal-strength schemes heavily [51].

1.2 Magnetic Induction for Wireless Sensors

Low-frequency magnetic induction is an *alternative propagation mechanism* to conventional radio. It uses antenna coils whose dimensions are significantly smaller than the employed wavelength. Such electrically small coils feature a very small radiation resistance and thus usually a small overall coil resistance (determined by the ohmic resistance of the coil wire). This allows to drive a strong current through a resonant[1] transmit coil with a given available transmit power, resulting in a strong generated magnetic field and strong induced currents at a resonant receive coil.

The chosen wavelength will often be larger than the intended link distance. In this case the receiver is in the near field of the transmit coil and the link amplitude gain h effectively scales like $h \propto r^{-3}$. This limits the usable range of low-frequency magnetic induction. Another disadvantage is that a low carrier frequency naturally limits the communication bandwidth and thus the achievable data rate.

Yet, in comparison to the described problems of conventional radio, low-frequency magnetic induction offers *various advantages* to wireless sensor technology:

1. Low-frequency magnetic fields *penetrate* various relevant *materials* (e.g. tissue, soil, water) with little attenuation [41, 54, 55] due to the large wavelength and favorable material permeability. Water for example hardly affects the magnetic field ($\mu_\mathrm{r} \approx 1$) but attenuates the electric field amplitude by a factor of $\epsilon_\mathrm{r} \approx 80$.

2. Low-frequency magnetic fields hardly interact with the environment and can thus be predicted by a free-space model [56–61]. Also, the amplitude gain of a magneto-inductive link is very sensitive to position and orientation of the transmit and receive coils (cf. $h \propto r^{-3}$) and thus bears rich geometric information. Magnetic induction is thus *suitable for accurate wireless localization.*

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[1] Many texts present resonance as a distinctive aspect of magnetic induction. However, we note that usually any radio antenna is operated at resonance in the sense that its electrical reactance is compensated by reactive matching circuits in order to maximize the antenna current for a given available transmit power [52, 53].

3. Increasing the *number of coil turns* is a very effective means of increasing the link gain in order to realize *strong mid-range links.* To some extend the number of turns can be increased while maintaining a coil geometry that is integrable into a device of *limited volume* (e.g. a cylindrical casing). No equivalent mechanism is available for electric antennas [62, Sec. 5.2.3].

4. At very low frequencies, the use of high-permeability *magnetic cores* can vastly increase the link gain.

5. With a low carrier frequency (i.e. a large carrier period time), *phase synchronization between distributed nodes* can feasibly be established. Cooperating sensors can then form a distributed antenna array for beamforming to achieve an array gain, a diversity gain, and possibly even a spatial multiplexing gain.

6. The severe path loss of near-field systems allows for vast *spatial reuse* and *security against remote eavesdropping* (e.g. for contactless payment with NFC).

The mere presence of a passive resonant coil can cause a significant alteration of the local magnetic field. This can be utilized to a technological advantage in various ways:

7. Inductive radio-frequency identification (RFID) tags use the effect for data transmission via *load modulation.* Thereby a tag modulates information bits by switching between two different termination loads for its coil. The receiver (an RFID reader) detects the field changes to decode the transmitted bits. [63]

8. One can place passive resonant coils between a transmitter-receiver pair in order to act as *passive relays*; a technique also known as magneto-inductive waveguide. The primary magnetic field generated by the transmit coil induces currents in the passive relay coils, giving rise to a secondary magnetic field which propagates to the receiver. This can improve the link. [64–68]

9. Significant link gain improvements can be achieved by putting a resonant passive relay coil right next to the transmit coil (coaxial and as a part of the transmitter device) and/or next to the receive coil (coaxial and as a part of the receiver device). Such *multi-coil designs*, which utilize the effect of strongly coupled magnetic resonances, allow for capable wireless power transfer systems. [69–75]

In summary, low-frequency magnetic induction with multi-turn coils is a suitable propagation mechanism for short- and mid-range power transfer, localization, and communication (either from an active transmitter or from a passive tag that uses load modulation). This holds especially for small devices in harsh propagation environments.

It furthermore allows for link improvements by placing passive resonant coils. Major drawbacks are the severe path loss and the small bandwidth. The low-frequency aspect is henceforth implied for magnetic induction and will not be pointed out repeatedly.

1.3 State of the Art, Open Issues, Contributions

1.3.1 Opening Remarks: Greater Goal and Focus

This dissertation is motivated by the greater (and currently open) problem of understanding the full capabilities of magnetic induction in the context of wireless sensors when the full technological potential is utilized. This problem context has been formulated in detail in the dissertation of Slottke [26]. A particularly interesting regime are small-scale applications with a potentially high node density such as medical microrobots. We desire a thorough understanding of the interplay of wireless powering, reach, radiation, achievable rates, the impact of coil arrangement and channel knowledge, outage and diversity, node cooperation, array techniques and mutual coupling, spatial degrees of freedom, passive relaying, miniaturization and high node density, as well as load modulation. A good understanding thereof would allow for an educated comparison to competing propagation mechanisms for medical microrobots, namely ultrasonic acoustic waves [76], molecular communication [24], and optical approaches [77].

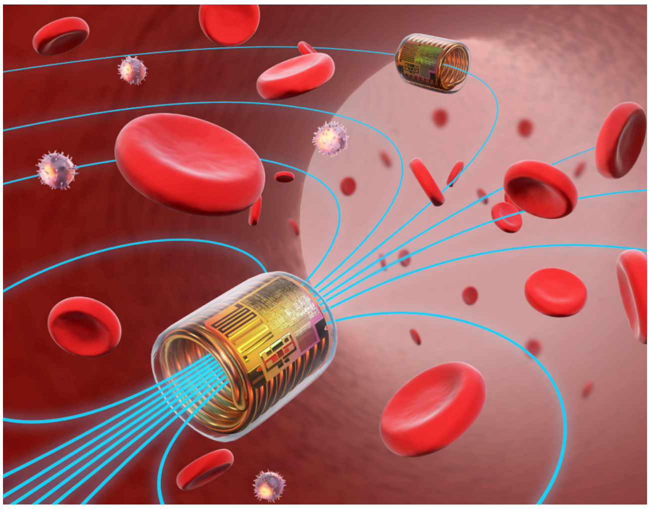

Figure 1.1: Concept art of several medical microrobots operating inside a blood vessel. They are equipped with a single-layer solenoid coil for wireless transmission and reception via magnetic induction. Integrated circuits for sensing and digital logic are indicated.

Clearly this greater problem divides into a multitude of subproblems, a subset of which will be addressed by the dissertation at hand. The remainder of the section describes this problem subset in detail, in relation to the current state of the art and with a focus on the physical layer and signal processing research literature.

1.3.2 Magneto-Inductive Coupling Models

State of the Art: All fundamental aspects of coil coupling are covered by classical electromagnetism; the general approach to coupling problems (e.g. via Maxwell's equations) is however associated with numerical approaches to partial differential equations [78]. Existing formal studies of communication or power transfer via magnetic induction (e.g., [65–68]) thus, to the best of our knowledge, all employ at least two simplifying assumptions: (i) the coils are electrically small and AC circuit theory applies, (ii) the magnetoquasistatic assumption, i.e. no radiation occurs whatsoever.

Identified Shortcomings: The magnetoquasistatic assumption requires that the wavelength exceeds the link distance by orders of magnitude. This limits a model's scope of validity and is particularly problematic because there is engineering incentive for choosing a small wavelength: using a larger frequency results in a larger induced receiver voltage. Furthermore, radiation can be desired to increase the reach (cf. midfield power transfer [75]) and to obtain an additional phase-shifted field component which could help against receive-coil misalignment. Radiation should thus be considered in the analysis of a magneto-inductive link, even for electrically small coils.

Chapter and Contribution: In Cpt. 2 we work out coupling formulas for electrically-small coils that do include radiation. In particular we present (i) a formula for arbitrary coil geometries and (ii) a dipole-type formula based on linear algebra, which allows for convenient interfacing with communication theory.

Associated Publications: The formulas appeared in our paper [79, Eq. 11 and 12] and the dipole formula was used in our paper on magneto-inductive localization [80].

1.3.3 Modeling and Analysis of Magneto-Inductive Links

State of the Art: The established approach to modeling magneto-inductive links uses an equivalent circuit description. This way the maximum power transfer efficiency between two coils (magnetoquasistatic regime) was stated by Ko [81, Eq. 6]. A rudimentary analysis of the channel capacity in thermal noise was given in [82] for coaxial coils and the assumption of a flat channel over the 3 dB-bandwidth of the system. They observe a rate-optimal coil Q-factor depending on the distance. Sun and Akyildiz studied magnetic induction with passive relaying for underground communication between coaxial coils in [41] and compared the approach to conventional radio for different soil conditions. They study the bit error rate of narrowband BPSK. In [65] they investigate the communication limits of underground networks of coplanar coils for various network topologies while exploiting the spatial reuse advantage. They use the 3 dB bandwidth as communication bandwidth and assume a flat channel thereover. The papers [83, 84] are dedicated to the optimization of technical parameters for capacity maximization of magneto-inductive channels, whereby the evaluation in [83] assumes a frequency-flat channel and noise spectral density over a heuristically chosen communication bandwidth. Kisseleff et al. [67, 85] formulate the channel capacity under due consideration of colored noise (thermal noise shaped by the receiver circuit) and the proper capacity-achieving spectral power allocation via waterfilling. They furthermore study practical digital transmission schemes over the frequency-selective (and thus time-dispersive) magneto-inductive channel in [86] and simultaneous wireless information and power transfer in [87]. The work in [88] investigates user cooperation for magneto-inductive communication.

Antenna arrays offer crucial advantages to wireless systems, namely array gain, diversity, and spatial multiplexing [89]. The use of arrays is thus vastly popular in radio communications [1, 2, 90] and has been proposed for magnetic induction for wireless power beamforming [91–93] and selection combining [94], underwater sensor networks [44], localization [59, 95–98], and beamforming for body-area sensor networks [99].

Identified Shortcomings: Simplifying assumptions are prevalent in the literature, e.g., the exclusive use of a dipole coupling model, narrowband assumptions, weak coupling, coaxial arrangement, thermal noise only, white noise, and heuristic spectral power allocation. The multi-stage transformer model [41,65,83] disregards coupling between non-neighboring coils but results in a more complicated formalism than a general approach (e.g. in terms of impedance matrices [26, 87, 100]). Most work assumes just a series capacitance as matching circuit even though it does in general not maximize power delivery from source to load.

A coil array usually exhibits mutual coupling among the associated coils. Such inter-array coupling has significant implications for matching and performance that are well-understood for MIMO radio communications [53, 101–103] but, to the best of our knowledge, are currently not considered by research on magnetic induction.

In conclusion, we identify the lack of a *well-structured general system model for* *magneto-inductive links* that would remedy the described shortcomings.

A related shortcoming is that load modulation has not received attention from communication theorists despite its use in disruptive RFID technology with great commercial success [63].

Chapter and Contribution: Cpt. 3 presents a concise and general system model for magneto-inductive communication and power transfer in any arrangement of transmitter (or transmit array) and receiver (or receive array). It accounts for array coupling, the statistics of noise signals from various sources, the desired matching strategy and its frequency-dependent effects. We state the channel capacity for narrowband and broadband cases, for a constraint on the available sum power or on the per-node powers. We discuss special cases such as weakly-coupled links, perfectly-matched links, orthogonal coil arrays as well as the associated degrees of freedom in detail. We furthermore present a treatise on cooperative load modulation with a reader array and the associated communication-theoretic performance limits.

Associated Publications: A summary of the MIMO system model appeared in our paper [79, Sec. II and III].

1.3.4 Impact of Arbitrary Coil Arrangement

State of the Art: The location of a wireless sensor is determined by its movement and the deployment strategy (which is either arbitrary or according to some application-specific criterion). In any case, the sensor position and orientation can be considered random by the communications engineer, which amounts to considering a random channel [83]. For magneto-inductive sensors an unfavorable coil orientation may result in severe link attenuation or outage. This trade-off between favorable coil arrangement and mobility has been noted in [33,83] and is the topic of [104] which studies the connectivity of magneto-inductive ad-hoc sensors. In [83] they identified the outage capacity as a meaningful performance measure of randomly arranged magneto-inductive communication links.

An appropriate coil coupling model provides a formal description of coil misalignment (i.e. the link attenuation due to deviations from coaxial arrangement), cf. Sec. 1.3.2. Most studies of coil misalignment are concerned with small lateral or angular deviations in the context of efficient short-distance power transfer [105–109]. The specific coil geometries must be considered in this regime, which complicates a mathematical analysis. At larger distances the much simpler dipole model (e.g. as stated in [67]) is appropriate.

Identified Shortcomings: The referenced studies [105–109] do not address the effect of a fully random coil orientation on the link gain, although this circumstance is to be expected for wireless sensors with high mobility such as medical microrobots. The impact of an arbitrary node orientation on the performance (and performance statistics) has not been studied so far, neither for single-input single-output (SISO) links nor for links with coil arrays. The need for an appropriate statistical channel model is highlighted by [110] who assumed a Rayleigh fading model for the effect of RFID coil misalignment because of the lack of a better model. Similarly, [83] worked with a Gaussian-distributed channel capacity with heuristically chosen variance.

The effect of coil arrays with a diversity combining scheme for misalignment mitigation so far (to the best of our knowledge) has also not been studied formally.

Chapter and Contribution: Cpt. 4 presents an analytic study of the statistics of the random fading-type channel that arises with random coil orientations (with a uniform distribution in 3D). The outage implications on the power transfer efficiency and channel capacity are investigated in detail. The SISO case is shown to exhibit catastrophic outage behavior: the diversity order is 1/2 for pure near-field or pure far-field propagation (even 1/4 for load modulation). The diversity order increases to 1 when both modes are present. The results are contrasted with the channel statistics for randomly oriented coil arrays after the application of a spatial diversity scheme.

Associated Publications: The channel statistics results for the pure near-field case with and without diversity combining appeared in our paper [111].

1.3.5 Magneto-Inductive Passive Relaying

State of the Art: Magneto-inductive passive relaying (as described in Item 8 of Sec. 1.2) was first proposed by Shamonina et al. [64] as a novel method of forming a waveguide. Thereby the relay elements were assumed in coaxial and equidistant arrangement between the transmitter and receiver coils. The merits of the concept for wireless powering or communication have been studied by [41, 65–68] for regular arrangements and with simplifying assumptions on the node couplings. For example, in [68] they analyze magneto-inductive communication over a 2-D grid of relays. The authors of [41, 65] consider only couplings between neighboring coils in networks of equidistant coplanar relays. The work contains an analysis of failure or misplacement of a single relay. The effect of coupling between non-adjacent relays in such a setup was studied in [66] for wireless power transfer. In [67] the communication performance of magneto-inductive relaying networks is optimized by adjusting the coil orientations for interference zero-forcing. The notion of random errors in relay deployment locations was introduced by [83] and its effect was investigated as part of [86]. The link SNR statistics for one randomly deployed relay were investigated in [26, Fig. 4.13]. Various researches pointed out the complicated effect of the relay density on the channel frequency response [41, 64, 83, 112, 113] and on the noise spectral density [114].

Identified Shortcomings: The literature on magneto-inductive passive relaying considers very specific regular arrangements or just small deviations thereof while simplifying assumptions on the node couplings are prevalent. We envision a cooperative scheme in (possibly very dense and arbitrarily arranged) magneto-inductive networks by which idle nodes may act as relays to improve the channel between the currently operating transmitter-receiver pair. Thereby we consider the node locations and orientations as completely arbitrary because sensor networks are often mobile or deployed in an ad-hoc fashion. The effects and technical merits of passive relays in such dense and random configurations are currently unknown and not described by any existing model. Dense swarms of nodes are of particular interest because they are an important envisioned use case for medical microrobots [115], where passive relaying might yield significant gains for magneto-inductive power transfer or communication.

Chapter and Contribution: In Cpt. 5 we analyze magneto-inductive passive relaying and its impact on the channel for arbitrary arrangements. Their effect is rigorously integrated into the system model of Cpt. 3 with one simple formula. A numerical evaluation of the channel statistics shows that randomly deployed relays cause frequency-selective fading: they can cause significant channel improvement or attenuation, depending on the density and individual geometric realization of the network. This is primarily caused by a non-coherent superposition of individual relay contributions to the link coefficient. The practical merits of such passive relay swarms are thus limited when a fixed operating frequency is used, but adapting the transmit signal to the frequency-selective channel allows for significant gains. For better utilization of the relays channel we study an optimization scheme based on the deactivation of individual relays by load switching and demonstrate considerable and reliable improvements.

Associated Publications: The content appeared in parts in our paper [116].

1.3.6 Magneto-Inductive Medical In-Body Sensors: Wireless Powering, Capabilities, Feasibility

State of the Art: Magnetic induction with its suitability for miniaturization and the other outlined advantages has been proposed for wireless-powered small-scale sensors with potential medical in-body applications [26, 117]. To this effect, the work of [26] contains an investigation on the miniaturization limits of magneto-inductive sensors. The authors of [118] discuss wireless powering of medical implants under consideration of tissue absorption. Coil designs for 4 mm-sized bio-implants and the resulting power transfer efficiency (PTE) in free space and tissue are presented in [119].

As discussed earlier, antenna arrays play a crucial role for modern wireless technology. The reach of energy-limited wireless nodes can be improved by forming a distributed array through user cooperation (e.g., see [28, 29, 88]), depending on the availability of channel knowledge and distributed phase synchronization.

Identified Shortcomings: The state of the art lacks an understanding of the behavior and performance capabilities of small magneto-inductive wireless nodes under exploitation of all technological aspects (arrays, cooperation, passive relaying, load modulation). This holds especially true for dense swarm networks, a relevant use case in envisioned applications of medical microrobots [22, 115] and an opportunity to the wireless engineer: physical layer cooperation between in-body devices allows for an array gain and spatial diversity in the uplink. Furthermore, dense swarms of strongly-coupled resonant coils can give rise to a passive relaying effect, associated with the complicated frequency-selective channel described in Sec. 1.3.5. These channel fluctuations should be exploited by the signaling scheme.

Chapter and Contribution: Cpt. 6 presents a technical evaluation of magnetic induction for small-scale in-body sensors. The sensors are assumed to receive power wirelessly and transmit data to a massive external coil array, which serves as data sink and power source (1 W). We discuss key aspects of the wireless channel and appropriate link design and compare propagation in muscle tissue to free space. For sensor devices 5 cm deep beneath the skin and an assumed 50 nW required chip activation power we project a minimum coil size of about 0.3 mm. However, a coil larger than 1 mm can be necessary depending on the data rate and reliability requirements as well as the availability of channel knowledge. We compare the cases of full channel knowledge, no knowledge, and sensor location knowledge. We find that an operating frequency of 300 MHz is suitable for this use case, although a much smaller frequency must be chosen if a larger penetration depth is desired. Moreover, we study resonant sensor nodes in dense swarms, a key aspect of envisioned biomedical applications. In particular, we investigate the occurring passive relaying effect and cooperative transmit beamforming. We show that the frequency- and location-dependent signal fluctuations in such swarms allow for significant performance gains when utilized with adaptive matching, spectrally-aware signaling and node cooperation. We show that passive relays are particularly capable in this context when their load capacitance is optimized and, furthermore, that load optimization can compete with active transmission if the receiving external device can measure with high fidelity (e.g., if thermal noise is the only impairment).

Associated Publications: Some of the content appeared in similar form in our paper [79, Sec. IV and V].

1.3.7 Magneto-Inductive Localization

State of the Art: In dense propagation environments, radio localization faces severe challenges from radio channel distortions such as line-of-sight blockage or multipath propagation [51, 120, 121]. Magnetic near-fields, in contrast, are hardly affected by the environment as long as no major conducting objects are nearby [56–61]. In consequence the magnetic near-field at some position relative to the source (a driven coil or a permanent magnet) can be predicted accurately with a free-space model. This enables the localization of an agent coil in relation to stationary coils of known locations (anchors) [58–61, 98]. In particular, position and orientation estimates can be obtained by fitting a channel model to measurements [59–61, 98]. The problem of estimating position and orientation of a single-coil agent or a permanent magnet was tackled least-squares estimation problem by [122–125]. Various system implementations for magneto-inductive localization have been published, e.g. [57–61].

Identified Shortcomings: The fundamental limits of magneto-inductive 3D localization are not addressed by existing research even though a rich set of tools for this purpose has been developed for radio localization [50, 126, 127].

The least-squares approach to position and orientation estimation with a gradient-based solver is slow and unreliable because the cost function is non-convex and has a five-dimensional parameter space. A fast and robust solution remains as an open algorithmic problem.

While magnetic induction presents the prospect of highly accurate localization (cf. Item 2 of Sec. 1.2) only mediocre accuracy is reported for practical systems, with a relative position error of at least 2% [57–61] (details are given in Cpt. 7). Thereby it is unclear which error source causes the accuracy bottleneck. Candidates are noise and interference, quantization, an inadequate signal model, the estimation algorithm, poor calibration, unconsidered radiation and field distortion due to nearby conductors.

Chapter and Contribution: In Cpt. 7 we first derive the Cramér-Rao lower bound (CRLB) on the position error for unknown agent orientation, based on the complex-valued dipole model from Cpt. 2 and a Gaussian error model. Therewith we study the potential localization accuracy on the indoor scale.

For this parametric estimation problem we find that numerical standard approaches are slow and often highly inaccurate due to missing the global cost function minimum. To this effect we design two fast and robust localization algorithms, enabled by a dimensionality reduction from 5D to 3D via eliminating the agent orientation parameters and by means for smoothing the cost function.

Based on these algorithms we present a system implementation with flat spiderweb coils tuned to 500 kHz. We evaluate the achievable accuracy in an office setting after a thorough calibration. During the calibration procedure we attempt to compensate field distortions and multipath propagation. The measurements are acquired with a multiport network analyzer, i.e. the agent is tethered and furthermore mounted on a controlled positioner device. We investigate the different sources of error and conjecture that field distortions due to reinforcement bars cause the accuracy bottleneck. Using the CRLB we project the potential accuracy in more ideal circumstances.

Associated Publications: Our paper [128] contains the proposed WLS3D algorithm and the CRLB result for the magnetoquasistatic case. These were generalized by our paper [80] which also presents the system implementation and evaluation.

1.3.8 Wideband Radio Localization

The work described in the following relates to wideband radio localization of wireless sensors in indoor environments with rich multipath propagation. It was conducted in the context of an industry project.

State of the Art: Most proposals for wireless radio localization rely on distance estimates to fixed infrastructure nodes (anchors) to determine the position of a mobile node [120], e.g. via trilateration. Cooperative network localization furthermore employs the distances between different mobile nodes [120, 121, 129, 130]. Given an exchanged radio signal between two nodes, a distance estimate can be obtained from the received signal strength (RSS) or the time of arrival (TOA).

Identified Shortcomings: RSS-based estimates have poor accuracy due to signal fluctuations [51, 131]. A TOA-based estimate can be very accurate but requires wideband signaling, a round-trip protocol for synchronization [50, 120] and involved hardware. It furthermore suffers from synchronization errors and processing delays [50, 132–134]. Yet the main problem is ensuring a sufficient number of anchors in line of sight (LOS) to all relevant mobile positions [135]. TOA thus exhibits a large relative error at short distances and is not well-suited for dense and crowded settings.

Chapter and Contribution: Cpt. 8 presents a novel paradigm for (short) distance estimation between ultra-wideband radio nodes in dense multipath environments, with various significant advantages over state-of-the-art indoor localization schemes. The scheme does not consider the channel between the two nodes whose distance is of interest but instead consider the presence an observer node. Consequently, the distance estimate is obtained by comparing the channels to that observer. We use the assumption of multipath components with random direction with a uniform distribution in 3D and, this way, utilize mathematical synergies with Cpt. 4.

Associated Publications: The content of Cpt. 8 appeared in our paper [136] and the core idea resulted in the patent applications [137, 138].

1.4 Acknowledgments and Joint Work

A number of people supported the creation of this thesis with technical advice and contributions. In particular I would like to express my gratitude to my supervisor Armin Wittneben for his guidance and countless crucial pointers, Robert Schober for acting as referee, Marc Kuhn and Henry Schulten for many important hints and discussions, Tim Rüegg for many things, Eric Slottke for advice on magneto-inductive technology and scientific computing, Yahia Hassan for advice on circuit theory and system modeling, Erwin Riegler and the contributors at stackexchange.com for mathematical consulting, Steven Kisseleff for fruitful discussions, and all collaborators listed in the following. Parts of Cpt. 5 emerged in collaboration with Eric Slottke. An earlier SISO-case variant of the system model in Cpt. 3 was used in [26] based on an earlier unpublished document [139] by the author of the thesis at hand (cf. [26, cited reference 33]). This work [139] comprised passive relaying evaluations of the kind [26, Fig. 4.9, 4.11, 4.12]. The collaboration with Henry Schulten in [140] laid the foundation of Appendix E. Cpt. 6 and Cpt. 7 benefited from simulations by Bertold Bitachon [141] and Bharat Bhatia [142], respectively. The localization system implementation in Cpt. 7 received valuable contributions by Christoph Sulser, Manisha De [143], Bharat Bhatia [144], and Henry Schulten. The idea of alternating position and orientation estimates in Cpt. 7 is from Wolfgang Utschick. The work on Cpt. 8 was supported by the Commission for Technology and Innovation CTI, Switzerland and conducted in cooperation with

Schindler Aufzüge AG. This ultra-wideband approach received inputs by Marc Kuhn, Malte Göller [145] and Robert Heyn and employed the ray tracer used in [127,135,146] which was graciously provided by the group of Klaus Witrisal at Graz University of Technology. Fig. 1.1 was created in collaboration with Philipp Gosch; a snippet was used on the cover of [26] with permission.

On a personal note, I would like to express my gratitude to my family for continuously supporting my endeavours. To my father Franz and sister Helga for introducing me to engineering and higher mathematics. To Rahel for much joy and comfort during the later PhD stages. To Armin, Marc and all colleagues at the Wireless Communications Group for their support, many life lessons, and fostering a constructive and respectful work culture. To my Telematik colleagues from TU Graz for the many spirited exchanges and their invaluable support. To the SPSC researchers at TU Graz for introducing us to the engineering sciences and the beautiful associated theories. To Alfred Strauß for imposing his emphatic reality checks on the Styrian youth and Joachim Maderer for a precious hard-line introduction to computer science. To every visitor and Signalöler for compensating the sometimes stuffy ways of Zurich. To everyone who supported my relocation, despite the turmoil. To the great scientists of ages past. To the taxpayers of Switzerland and Austria for funding my education and research. And finally I want to thank all the keen people at the ITET department and the IEEE for tirelessly advancing our field.

Chapter 2

Essential Physics for Electrically Small Coils

In Sec. 1.3.2 we argued that radiative propagation modes should be included in a magneto-inductive coupling model, even if the involved coils are electrically small (i.e. much smaller than the employed wavelength). To this effect, Sec. 2.1 derives respective formulas for the mutual impedance between coils. We furthermore state necessary coil self-impedance formulas for relevant coil geometries in Sec. 2.2 and a description of coil interaction in terms of impedance matrices in Sec. 2.3. The exposition is preceded by a wrap-up of the essential physics.

2.1 Mutual Impedance Between Wire Loops

When an electric current i_T (complex-valued phasor, unit ampere) is applied at the terminals of a transmit antenna, the resulting induced voltage at a receive antenna is

$$v_\mathrm{R} = Z_\mathrm{RT}\, i_\mathrm{T} \tag{2.1}$$

where Z_RT is the complex-valued *mutual impedance* Z_RT (a.k.a. transimpedance) between the two antennas. It is a key quantity for the description of a wireless link. This section is concerned with mathematical descriptions of Z_RT between two coils, given their wire geometries and relative posture. The situation is illustrated in Fig. 2.1. The specific objectives of this section are:

- Providing an insightful derivation of the general formula (2.16) for Z_RT between electrically small thin-wire coils, comprising near- and far-field propagation.
- Introduction of the simple linear-algebraic formula (2.23) for Z_RT, valid for coils whose turns have consistent surface orientation and for link distances appreciably larger than the coil dimensions.

Before we dive into details about magnetic induction we want to wrap up key principles of electromagnetism in order to recall the mechanisms and establish the

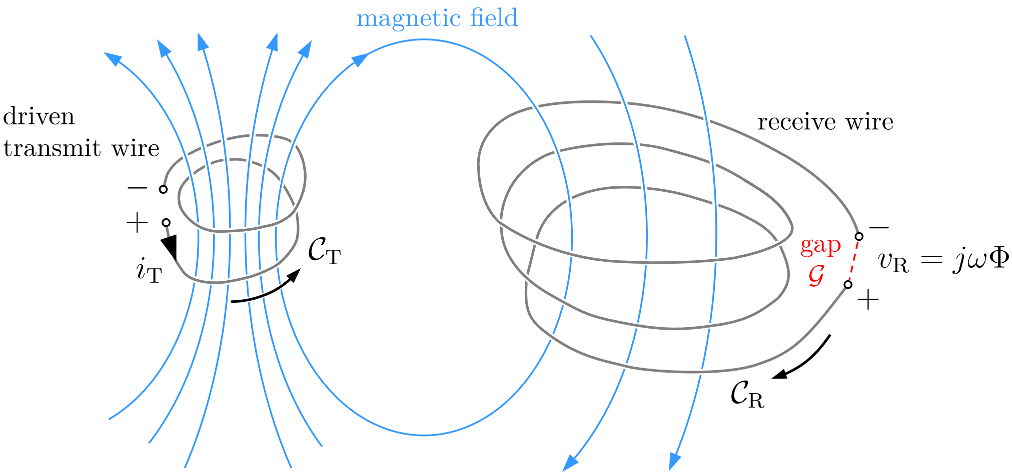

Figure 2.1: A basic magneto-inductive link. A current i_T drives the transmit coil wire whose geometry is described by the one-dimensional smooth curve $\mathcal{C}_\mathrm{T}$ (whose direction is illustrated as well). The induced voltage v_R is measured between the terminals of the smooth curve $\mathcal{C}_\mathrm{R}$, which describes the geometry of the receive coil wire.

notation. All quantities are in SI units. It is assumed that the reader is familiar with vector fields over space and time and with the basiscs of vector calculus such as the curl and divergence of fields as well as line and surface integrals.

Electromagnetism describes the forces on electrically charged particles due to the presence and movement of other electrical charges (the so-called field sources). Wireless systems use this mechanism in the fashion "move electrons at the transmitter to make electrons move at the receiver". In particular, the force $\vec{F} = q\,(\vec{E} + \vec{v} \times \vec{B})$ applies to a particle with electrical charge q and velocity $\vec{v}$ where $\vec{E}$ and $\vec{B}$ are the electric and magnetic field, respectively, at the particle position [147, Cpt. 18]. These fields arise due to the field sources, which are described by the volume charge density ϱ and the current density $\vec{J}$. Calculating $\vec{E}$ and $\vec{B}$ from given ϱ and $\vec{J}$ over space and time is a difficult problem; a complete framework to do so is given by Maxwell's famous four equations [148, 149] which are well-documented in modern physics literature [147] and wireless engineering literature [52, 62, 150, 151]. To describe Maxwell's equations in a nutshell, charges are sources and sinks of $\vec{E}$ according to the divergence $\nabla \cdot \vec{E} = \varrho/\varepsilon_0$ while $\vec{B}$ has no such sources or sinks, i.e. $\nabla \cdot \vec{B} = 0$. The law $\nabla \times \vec{B} = \mu_0(\vec{J} + \varepsilon_0\, \partial\vec{E}/\partial t)$ states that a solenoidal $\vec{B}$-field arises around a current or around a time-variant electric field (hence called a displacement current). Finally, by the law of induction $\nabla \times \vec{E} = -\partial\vec{B}/\partial t$ from Faraday [152], a solenoidal $\vec{E}$-field arises around a time-variant magnetic field.

For most purposes in wireless engineering the above laws are unnecessarily general and a description for harmonic quantities at some radial frequency $\omega = 2\pi f$ suffices.

Following the proposal of [52, Eq. 1.14] we write Maxwell's equations in phasor notation

$$\nabla \cdot \mathbf{e} = \rho/\varepsilon_0 \ , \tag{2.2}$$

$$\nabla \cdot \mathbf{b} = 0 \ , \tag{2.3}$$

$$\nabla \times \mathbf{e} = -j\omega\, \mathbf{b} \ , \tag{2.4}$$

$$\nabla \times \mathbf{b} = \mu_0 \left(\mathbf{j} + j\omega\, \varepsilon_0 \mathbf{e} \right) \tag{2.5}$$

in terms of complex-valued phasors $\mathbf{e}$, $\mathbf{b}$, ρ, $\mathbf{j}$. The original quantities relate to the phasors via

$$\vec{B} = \sqrt{2}\ \mathrm{Re}\{\mathbf{b} e^{j\omega t}\} \tag{2.6}$$

and so forth. Thereby e is Euler's number and j is the imaginary unit. An overview of the relevant quantities for the following exposition is given in Table 2.1.

Symbol	**Set or Value**	**Description**
i_T	$\mathbb{C} \cdot \mathrm{A}$ (ampere)	transmit current phasor
v_R	$\mathbb{C} \cdot \mathrm{V}$ (volt)	receive voltage phasor
ρ	$\mathbb{C} \cdot \frac{\mathrm{C}}{\mathrm{m}^3}$	charge density phasor
$\mathbf{j}$	$\mathbb{C}^3 \cdot \frac{\mathrm{A}}{\mathrm{m}^2}$	current density phasor
$\mathbf{e}$	$\mathbb{C}^3 \cdot \frac{\mathrm{V}}{\mathrm{m}}$	electric field phasor
$\mathbf{b}$	$\mathbb{C}^3 \cdot \frac{\mathrm{V \cdot s}}{\mathrm{m}^2} = \mathbb{C}^3 \cdot \mathrm{T}$ (tesla)	magnetic field (a.k.a. flux density) phasor
Φ	$\mathbb{C} \cdot \mathrm{V} \cdot \mathrm{s}$	magnetic flux phasor
φ	$\mathbb{C} \cdot \mathrm{V}$	electric potential phasor
$\mathbf{a}$	$\mathbb{C}^3 \cdot \mathrm{T} \cdot \mathrm{m}$	magnetic vector potential phasor
$\mathcal{C}_\mathrm{T}$	$\subset \mathbb{R}^3 \cdot \mathrm{m}$, $\dim(\mathcal{C}_\mathrm{T}) = 1$	directed curve, describes transmit wire
$\mathcal{C}_\mathrm{R}$	$\subset \mathbb{R}^3 \cdot \mathrm{m}$, $\dim(\mathcal{C}_\mathrm{R}) = 1$	directed curve, describes receive wire
r	$\mathbb{R} \cdot \mathrm{m}$	distance between wire points
$d\boldsymbol{\ell}$	$\mathbb{R}^3 \cdot \mathrm{m}$	directed length element
$d\mathbf{s}$	$\mathbb{R}^3 \cdot \mathrm{m}^2$	directed surface element
μ_0	$\approx 4\pi \cdot 10^{-7}\, \frac{\mathrm{T \cdot m}}{\mathrm{A}}$	vacuum permeability [153, App. 2]
ε_0	$\approx 8.854 \cdot 10^{-12}\, \frac{\mathrm{C}}{\mathrm{V \cdot m}}$	vacuum permittivity
c	$= \frac{1}{\sqrt{\mu_0 \varepsilon_0}} \approx 3 \cdot 10^8\, \frac{\mathrm{m}}{\mathrm{s}}$	vacuum speed of light

Table 2.1: Overview of the relevant physical quantities of Sec. 2.1. Every complex phasor quantity x represents a harmonic signal $X(t) = \sqrt{2}\ \mathrm{Re}\{x e^{j\omega t}\}$ whereby both x and $X(t)$ are position-dependent, which is not denoted explicitly. The factor $\sqrt{2}$ ensures that $|x|^2$ equals the mean square value of $X(t)$. The same conversion rule $\vec{X}(t) = \sqrt{2}\ \mathrm{Re}\{\mathbf{x} e^{j\omega t}\}$ holds between a field vector $\vec{X}$ and its complex phasor representation $\mathbf{x}$.