称号及び氏名	博士（工学）　Nguyen Anh Huy
学位授与の日付	2019 年 3 月 31 日
論　　文　　名	「 Performance improvement of periodic flows in multi-hop wireless sensor networks 」
論文審査委員	主査　　戸出　英樹 副査　　宇野　裕之 副査　　黄瀬　浩一

論文要旨

In recent years, the demand for wireless networks treating various types of periodic flows increased, for example, wireless sensor networks (WSNs) for healthcare, smart meter networks, or structural health. Particularly, in healthcare networks, there are numerous periodic data flows, such as blood pressure, heart rate, and blood oxygenation level. In such wireless networks treating periodic flows, the following problems must be solved.

Firstly, periodic flows cause the inherent problem of continual packet collisions, which results in successive packet losses and decrease in communication quality. Specifically, if the packet generation timing on different source nodes overlaps, packet collisions among the different interfering flows occur continually, until the interfering sessions are terminated. Although the IEEE 802.11 distributed coordination function (DCF) fixes packet collisions, its random backoff to avoid subsequent packet collisions and retransmission reduces network effective bandwidths, which results in packet loss due to network congestion. Additionally, the

workloads for relay nodes increase due to the retransmission and timer expiration processes. Therefore, another collision avoidance mechanism to deal with periodic flows is required.

Secondly, given a large number of sensor nodes placed in a large area, hidden node problem is the problem that occurs when a node (node A) is visible to a node (node B) but not to other node (node C) which is communicating with node B. When these nodes are in hidden node topology, if node C is transferring packet to node B, and node A also start transferring packet to node B, a collision occurs. This collision will not happen if node A also is in range of node C and thus knows that node C is transferring its packet to node B. Hidden node problem also becomes serious in addition to general contention between data flows. Moreover, once periodic packet transmission phases are synchronized among different periodic data flows, they will contend continually.

Many existing protocols that schedule the timing of sending packets are based on time division multiple access (TDMA). However, TDMA is not widely spread for the following reasons. First, the installation cost of nodes is expensive. Second, TDMA is not suitable for dynamically changing network environments and TDMA-based systems need complicated controls, such as time synchronization.

This thesis attempts to propose methods to improve the performance of periodic flows in wireless sensor networks (WSNs). Furthermore, we try to avoid the constraints of the related work such as time synchronization and high installation cost.

As for the detailed content, this thesis is organized as follows:

In Chapter 1, we show the research overview of this thesis. We also describe the problems and some related solutions. In particular, this thesis will focus on two problems, the inherent problem of continual packet collisions and the compounded effect of the hidden node and the continuous collision problems.

In Chapter 2 and Chapter 3, we tackle the first challenge of this thesis which is the problem of continual packet collisions by shifting the packet generation timing. In Chapter 2, we propose a simple method to choose the shift-time. The simulation in single-hop network environment shows the positive results.

In Chapter 3, we propose a new formula for predicting whether two heterogeneous periodical flows from different source nodes have overlapping packet transfer durations. From this formula, we propose transfer scheduling methods that shift the packet generation phase (timing) to avoid future collisions. These methods adopt naive random-access control, like DCF, for the MAC layer process. In addition, source nodes do not require significant computational power, because only the sink intensively schedules the timing and informs to the corresponding source. Therefore, compared to existing methods in which each source node completely schedules the timing of creating packets based on TDMA, our methods require less functional expansion, complexity, and computational power. Finally, we demonstrate the effectiveness of our methods through simulation in both single and multi-hop environments.

As the next challenge, in Chapter 4, this thesis tackles a compounded negative effect of the hidden node problem and a continuous collision problem among periodic data packet flows in WSNs. This is not a simple and well-studied solution for just the hidden node problem but the compounded problem. With the rapid increase in IoT (Internet of Things) applications, more sensor devices, generating periodic data flows whose packets are transmitted at regular intervals, are being incorporated into WSNs. However, packet collision caused by the hidden node problem becomes serious particularly in large-scale multi-hop WSNs. Moreover, focusing on periodic data flows, continuous packet collisions among periodic data flows are caused once periodic packet transmission phases are synchronized. To address this challenge, we propose a new MAC layer mechanism. The proposed method predicts a future risky duration during which collision can be caused by hidden nodes by taking into account periodic characteristics of data packet generation. In the risky duration, each sensor node stops the transmission of its data packets in order to avoid collisions. To the best of our knowledge, this is the first work that considers the compounded effect of hidden nodes and continuous collisions among periodic data flows. Other advantages of the proposed method include that any new control packets are not required and it can be implemented in widely-diffused IEEE 802.11 and IEEE 802.15.4 devices.

Finally, in Chapter 5, we conclude the thesis and discuss about the future work.

審査結果の要旨

本論文は，将来，積極的な応用が期待される IoT（Internet of Things）を包含する単一段もしくは多段の無線センサー網において，各端末ノードから発生する異なる周期のデータフロー間における連続的なパケットの衝突問題を解決し，各センサーノードの転送性能を改善することで，快適なセンシングアプリケーションの実現をめざす研究であり，以下の成果を確認した.

(1) 個々のセンサーノードから発生する周期的なパケットフロー間の連続衝突発生問題を，ソース・シンクノード間のアプリケーション層レベルの End-to-End 制御で解決するため，ソースノードからのデータ転送時間を仮想的な時分割多重を想定した離散時間タイミングに合わせてシフトさせる BDM（Binary Division Method）方式を提案した. シミュレーション実験を通じて，シンプルな制御機構にかかわらず，本方式が小規模な端末ノード数条件下で良好な転送性能を示すことを実証した.

(2) 周期フロー間の連続衝突発生問題をさらに効率的に解決するために，2 つの異なるソースノードから発生する異なる周期のパケットフロー間でパケット転送時間の重複が発生することを予測するための数式を理論的に導出した. また，この数式に基づき，各ソースノード間のパケット送出タイミングをスケジューリングするプロトコル CSM（Collision Score Method）方式を提案した. シミュレーション実験を通して， End-to-End のアプリケーション層で実装可能なシンプルな機構であるにも関わらず，本方式が特に短期間通信のアプリケーションに対してさらに優れた転送性能を達成できることを実証した.

(3) 多段無線センサー網における各種周期パケットフローからのデータ集約において，センサーノードの信号伝搬範囲の制約に起因して発生する隠れ端末問題に対処し，将来の衝突を検知，予測，そして回避するための新たな MAC(Medium Access Control)層制御機構 PHT（Prediction of Hidden Transfer）方式を提案した. PHT 方式では固定誤差マージンと適応的誤差マージンの 2 種類の実装法 PHTS,PHTA が規定され， PHTS はシンプルで計算量が少なく，PHTA はより優れた性能を達成する. シミュレーション実験を通して，本方式が，パケット廃棄率の劇的な改善に加え，センサーノード間の性能の公平性をも達成できることを実証した.

(4) PHT 方式とアプリケーション層レベルのデータ転送スケジューリング手法である BDM 方式，および CSM 方式を同時に適用可能であることを示し，これによりパケット廃棄率性能が最大限に改善されることを明らかにした.

以上の諸成果は，IoT を含む，単一段および多段無線センサー網の高品質なデータ転送の実現に大いに貢献すると考えられ，本分野の学術的・産業的な発展に貢献するところ大である. また，申請者が自立して研究活動を行うのに必要な能力と学識を有することを証したものである.