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論文内容の要旨

Delay tolerant networks (DTNs) provide networking in infrastructure-less environments, e.g., deep space, rural areas, disaster areas, underwater fields, etc. In DTNs, the current TCP/IP model cannot work well due to lack of continuous end-to-end connectivity. A *store-carry-forward* message delivery scheme and *custody transfer* mechanism is used in DTNs to confirm reliable transfer of bundles with custody among nodes, by delegating the responsibility of custody-bundle transfer through intermediate nodes in a hop-by-hop manner. Note that a bundle is the protocol data unit in DTNs. The intermediate nodes keeping custody bundles are called *custodians*. Each custodian must reserve a sufficient amount of storage and energy for receiving and holding the custody bundles until their successful delivery or delivery expiration. Due to shortage of storage capacity, custodians sometimes face storage congestion, where they have to refuse to receive any custody bundle from other nodes. In addition, each battery-powered node has to be awake while holding the bundles. Since each custodian also generates its own custody bundles, it is naturally selfish in behavior and rejects requests of custody transfer from other nodes to save its storage as well as its energy. Intuitively, this problem is aggravated in long-term isolated networks.

In such a situation, some movable vehicles referred to as *message ferries* can solve the storage congestion problem by actively visiting the network and gather bundles from custodians. Note that message ferries are equipped with a storage enough to carry collected bundles to the destination, i.e., a base station referred to as a *sink node*, and it can also supply energy to the custodians if required. When there are multiple isolated networks referred to as *clusters*, message ferries have to periodically visit those clusters and collects bundles from custodians there. This network architecture is suitable for wide area sensing. Note that each node in a cluster

can directly/indirectly communicate with other cluster members through multi-hop communication but cannot communicate with nodes in other clusters due to long distances among them. A message ferry helps the inter-cluster communication by acting as a mediator between each cluster and the outer world via the sink node which serves as a connector to the Internet or to other sink nodes.

In such ferry-assisted multi-cluster scenario, inter-cluster communication and intra-cluster communication should be carefully considered to minimize the total mean delivery delay of bundles. This thesis mainly focuses on these inter-cluster and intra-cluster communications by combining three research studies. The inter-cluster communication has been studied by two studies: 1) Grouping clusters, and 2) Optimal visiting order of isolated clusters. And, the intra-cluster communication has been studied by self-organized data aggregation technique among selfish nodes in an isolated cluster.

Thesis Organization:
The content of this thesis is organized into following five chapters:

1. Introduction
2. Self-organized data aggregation technique
3. Optimal visiting order of isolated clusters
4. Grouping clusters
5. Conclusion

Chapter 1 provides the background of recent development of DTNs, the motivation for the studies and the aim of the research.

Chapter 2 addresses intra-cluster communication by self-organized data aggregation technique among selfish nodes in an isolated cluster. We proposed a self-organized data aggregation technique for collecting data from nodes efficiently, which can automatically accumulate data from nodes in a cluster to a limited number of nodes (called aggregators) in the cluster. The proposed scheme was developed based on the evolutionary game theoretic approach, in order to take account of the inherent selfishness of the nodes for saving their own battery life. The number of aggregators can be controlled to a desired value by adjusting the energy that the message ferry supplies to the aggregators. We further examine the proposed system in terms of successful data transmission, system survivability and the optimality of aggregator selection. We introduce two game models by taking account of the retransmissions mechanism of bundles. Through both theoretical and simulation-based approaches, we reveal feasible parameter settings that can achieve a system with desirable characteristics of stability, survivability, and successful data transfer.

Chapter 3 focuses on one part of inter-cluster communication by studying the optimal visiting order of isolated clusters. When there are lots of distant static clusters, the message ferry should visit them efficiently to minimize the mean delivery delay of bundles. We propose an algorithm for determining the optimal visiting order of isolated static clusters in DTNs. We show that the minimization problem of the overall mean delivery delay in our system is reduced to that of the weighted mean waiting time in the conventional polling model. We then solve the problem with the help of an existing approach to the polling model and obtain a quasi-optimal balanced sequence representing the visiting order. Through numerical examples, we show that the proposed visiting order is effective when arrival rates at clusters and/or distances between clusters and the sink are heterogeneous.

Chapter 4 focuses on another part of the inter-cluster communication by studying the grouping of clusters. When there are lots of distant static clusters, multiple message ferries and sink nodes will be required. We aim to make groups each of which consists of physically close clusters, a sink node, and a message ferry. Our main objective is minimizing the overall mean delivery delay of bundles in consideration of both offered load of clusters and distance between clusters and their sink nodes. We first model this problem as a nonlinear integer programming, based on the knowledge obtained in our previous work. Because it might be hard to solve this problem directly, we take two-step optimization approach based on linear integer programming, which yields an approximate solution of the problem. Through numerical results, we show the two-step optimization approach works well.

Chapter 5 presents the conclusions of this thesis by summarizing all results and observations we obtained through the researches.

論文審査の結果の要旨

現在のインターネットはTCP/IPを基礎としているため，エンドホスト間の通信路が常時確保できることが前提となっている．近年，このような前提が成立しない環境下でも通信を可能にする，耐遅延ネットワーク（DTN: Delay Tolerant Networks）と呼ばれる技術に注目が集まっている．

本論文は，DTNの一技術であるメッセージフェリーを用いたネットワーキング技術に関する研究をまとめたものである．想定されている環境は，クラスタと呼ばれる端末群が多数，地理的に分散し，クラスタ間で互いに直接，通信が行うことができないという状況である．本論文では，クラスタを複数のグループに分け，各グループ毎にグローバル網の接続が可能である基地ノードとメッセージフェリーと呼ばれる移動型端末を割り当て，メッセージフェリーをグループ内のクラスタを巡回させることで，エンドホストのグローバル網への効率的なアクセスを実現するシステムの設計手法を論じている．主たる研究成果の要約は以下の通りである．

（1）クラスタ内のエンドホストはマルチホップ無線通信によって通信可能であるという前提の下で，メッセージフェリーが個々のクラスタを訪れた際，効率的にクラスタ内のエンドホストから発生したデータをメッセージフェリーへ送信するために，自律分散的にクラスタ内の少数のエンドホストへデータを集める手法を進化ゲーム理論を援用して開発した．さらに，その手法の特性を数学モデルの解析並びにシミュレーション実験を通じて明らかにし，その有効性を示した．

（2）基地ノードが置かれたクラスタ（基地クラスタ）とその基地ノードを利用する他のクラスタ群からなるグループが与えられたとき，メッセージフェリーが基地クラスタと他のクラスタを交互に訪問するという仮定の下で，平均転送遅延を最小とするメッセージフェリーの巡回順序の準最適解を決定するアルゴリズムを開発した．数値実験を通じて，各クラスタと基地クラスタの間の時間距離に差があり，かつ，各クラスタのトラヒック強度に差がある場合，従来から検討されていた巡回セールスマン問題の解に基づく手法と比較して，平均転送遅延が大きく改善されることを示した．

（3）地理的に分散した多数のクラスタが与えられたとき，それらを複数のグループへ分割し，個々のグループにおける基地クラスタを決定するアルゴリズムを開発した．クラスタのグループ化に対する評価指標は，上記（2）に基づいてメッセージフェリーを各グループ内で巡回させた際に得られる平均転送遅延であり，これを目的関数とした非線形整数計画問題を定式化した．さらに，この問題の近似解を得るために，2段階の線形整数計画問題を定式化し，これらを解くことで，効率的なグループ分けを行えることを示した．

以上のように，本論文はメッセージフェリーを用いたネットワーキング技術に関して，多数の有用な知見を与えており，情報通信工学の発展に寄与するところが大きい．よって本論文は博士論文として価値あるものと認める．